SMALL SCALE CONSTANT-AREA TEST OF AN AEROTHERMOPRESSOR

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JAMES COBB MATHESON

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by

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Submitted in Partial Fulfillment of the

Requirements for the Degree of

NAVAL ENGINEER

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ABSTRACT

A theoretical one-dimensional analysis of a hot gas stream indicates that a stagnation pressure rise may be attained by the evaporation of water in the stream for supersonic and subsonic flow. An aerothermopressor is a gas pumping device operating on this principle. The purpose of this investigation is to obtain experimentally in a small scale test, data on the operating characteristics of the aerothermopressor for use in the design of an effective working model. One practical application of an aerothermopressor is its use as a means of improving the efficiency of a gas turbine. The pumping effect of the device would permit a lower turbine back pressure than could be obtained from conventional atmospheric exhaust.

Experiments were conducted on test equipment consisting of a hot gas source, a converging-diverging nozzle for acceleration of the heated gas, a 36" - 1.525" I.D. constant area evaporation section and an exit tank. Flow was established by means of a laboratory air ejector. Data was measured with this apparatus at Mach numbers in the region of 2.0 and 0.4 at inlet temperatures up to 1500°R, with varying rates and positions of axial water injection. With the aid of theoretical analysis, efforts were made to determine the effect on operation of temperature, rate and position of injection, amount of evaporation and the influence of friction.

The small diameter of the test section and absence of a diffuser introduce losses which preclude a net stagnation pressure rise. However, the injection and evaporation of water was observed to appreciably raise the exit stagnation pressure above the pressure attainable without water injection. Subsonic runs demonstrated a greater amount of evaporation per unit length and greater capacity for evaporation than the supersonic runs. In either case a length of approximately four feet is necessary to permit complete evaporation at saturated exit conditions. Wall friction effects in small diameter test sections are critical. The effective friction factor increases with rate of injection and varies with length within the test section. The mean friction factor in wet runs may exceed the dry run value by 50%.

Further tests at higher subsonic Mach number, utilizing a converging nozzle, and test section twice the present diameter are recommended. They are considered possible with present laboratory facilities.

The success of a full scale aerothermopressor is believed limited principally by wall friction. The promise of wall friction reduction with increased evaporation section diameter is encouraging.

Thesis Supervisor: A. H. Shapiro
Title: Professor of Mechanical Engineering

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The authors wish to express their appreciation to Professor A. H. Shapiro for the suggestion of this investigation and for his advice and assistance in guiding the project. The authors are also grateful to Professor K. R. Wadleigh for his aid in the theoretical analysis and to the Boston Naval Shipyard and the personnel of the Massachusetts Institute of Technology Gas Turbine Laboratory for their assistance with the experimental phase of the work. The authors are also appreciative of the suggestions of Professor R. Dean and Professor L. R. Vianey.

Cambridge, Massachusetts
16 May 1952

Secretary of the Faculty
Massachusetts Institute of Technology
Cambridge, Massachusetts

Dear Sir:

In accordance with the requirements for the degree of Naval Engineer, we submit herewith a thesis entitled, "Small Scale Constant-Area Test of an Aerothermopressor".

Respectfully,

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I. INTRODUCTION

An aerothermopressor* is a device designed to raise the stagnation pressure of a gas stream by lowering the stagnation temperature through the evaporation of a liquid. It is, in effect, a pump with no moving parts. The promise of such a device is demonstrated by Shapiro and Hawthorne(1). They further point out that this effect cannot be expected with a heat exchanger, since the inherent nature of friction and heat transfer as seen from the Reynolds Analogy, makes any net stagnation pressure rise impossible.

Shapiro and Wadleigh(2) have analyzed the constant area, constant pressure, constant Mach number, and constant temperature processes as applied to the aerothermopressor. Hawkins and Mowell(3) have obtained data for the supersonic constant temperature case, and Templeton and Wish(4) provided a theoretical analysis of the results. Curry(5) has obtained data for the subsonic constant area process.

A suggested application of this device is its use in increasing the efficiency of a gas turbine installation by virtue of its pumping effect. An aerothermopressor fitted to the discharge of such a turbine would permit expansion of the turbine gases to below atmospheric pressure. The power required to return the gas to atmospheric pressure in such an installation would be provided by the relatively inexpensive evaporation of water.

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*This device is termed an aerothermoprex in some other studies.

(1)All superscripts noted thus refer to references in the bibliography of the appendix.

This investigation covered the small scale test of an aerothermopressor with a constant area test section at both supersonic and subsonic flow rates. Since no previous data had been obtained on the constant area supersonic process, this investigation was conducted with that as a principle objective. However, the experimental installation was so designed as to permit both supersonic and subsonic tests.

It is noted that the process chosen is not that suggested by Shapiro and Hawthorne(1) for optimum performance. Further, the frictional effects in such a small scale model, and the absence of a suitably designed diffusser at the test section exit introduce losses which preclude any net stagnation rise in the apparatus. However, since the major concern was the study of effects, rather than successful operation as an aerothermopressor, the constant area process was chosen as most suitable for evaluation of the effects of the various process variables. Specifically, it was desired to obtain data relating the effects of the position of water injection, initial gas stream temperatue, rate of water injection, rate of evaporation and friction. It is expected that this information will be utilized in the subsequent design of a full scale unit to be tested at M. I. T.

II. PROCEDURE

A. Design:

The design of the test apparatus embodied a compromise between the available air ejector capacity of the Gas Turbine Laboratory and the desire to obtain both subsonic and supersonic data from a single nozzle-test section design.

For the purpose of this investigation, the exhaust gases from a propane gas furnace were used as the hot gas source and the air ejector was used to provide the downstream subsonic pressure. It was decided to use a circular cross-section test section, and to make the diameter as large as practical within the mass flow rate limits of the furnace and air ejector to minimize friction losses. It was further decided to make the test section as long as possible, within the limits of choking in supersonic flow, to permit maximum evaporation. The selection of a Mach number for supersonic operation dictated the area ratio of the throat and test section and consequently fixed the maximum subsonic Mach number at which the test section could operate. The supersonic Mach number selection also dictated the permissible length of test section that could be used free of choking.

From previous test data[3], the gas furnace was known to have a capacity of about 0.2 pounds of air per second at 1500° Rankine. The air ejector pressure for this mass flow was 2.0 psia. Calculated friction losses from the ejector to the test section was 0.5 psia. This made available a 14 psia drop across the nozzle and test section which provided adequate operating margin.

Table I in the appendix indicates the analysis made to determine the length of test section, mass rate of flow and test section Mach number. From this analysis, which is amplified in Appendix A, the following characteristics were used for the nozzle and test section:

Mass Rate of Flow	0.214 lbs. of air/second
Test Section Supersonic Mach number	2.0
Diameter of Test Section	1.525"
A/A* Ratio	1.6875

The characteristics permitted operating the nozzle and test section in subsonic flow at a Mach number of 0.3.

B. Operating Equipment:

The equipment usedto obtain data is shown in Figure I. Figure II is a diagrammatic sketch of the test setup with indicated flow symbols. The actual aerothermopressor consists of the nozzle, test section and water injection apparatus; all other equipment is incident to operation and data measurement. The temperature of the exhaust gases was varied by means of the pressure control valve at the propane bottle. Operation was restricted to the 1100°-1500° Rankine range to simulate gas turbine outlet conditions although higher temperatures were attainable. The hot gases flowed from the furnace into the upper stagnation chamber, through the nozzle and through the vertical test section (1.525" I.D. copper-nickel seamless tubing). From the test section, the gases flowed through the lower stagnation chamber to the ejector tank from which the air ejector took its suction.

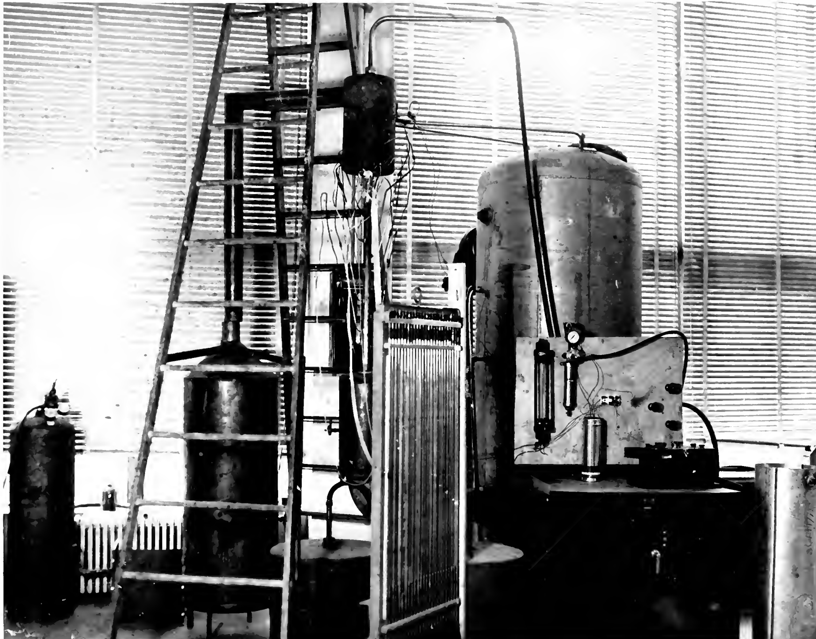
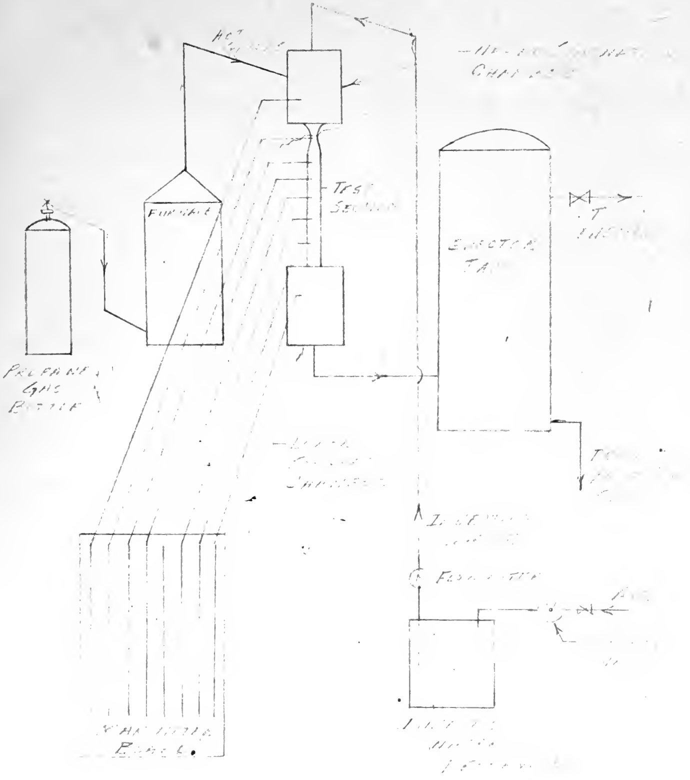


FIGURE I

ARRANGEMENT OF TEST EQUIPMENT

FIGURE II



The upper stagnation chamber housed the water injection tube -a 1" stainless steel tube with six 6" long 0.025" I.D. hypodermic tubes in the end. The injection tube was adjustable axially and could be positioned to give water injection at various positions from entrance to the exit of the nozzle.

The water spray between the lower stagnation chamber and the ejector tank was used in the subsonic runs to obtain more precise control of test section exit pressure. The air ejector tank served as a water collection tank and was drained by gravity head to the laboratory basement sump.

C. Instrumentation:

Chromel-Alumel thermocouples were used for measuring the temperatures in the upper and lower stagnation chambers. The junction of the upper stagnation chamber thermocouple was shielded by a thin C.R.S. cylinder but the junction of the lower stagnation chamber thermocouple was unshielded. The potentionometer conversion table is shown graphically in Figure XXIX of Appendix A.

Static pressure taps feeding to a standard mercury manometer board were located at 3" intervals along the test section, at the nozzle throat and exit, in the upper and lower stagnation chambers and in the ejector tank. An impact tube was placed in the lower stagnation chamber to indicate velocity magnitude at that point.

The water injection rate was measured by means of the flowmeter. The flowmeter calibration chart is included as Figure XXX in the appendix.

D. Operating Procedure - Supersonic:

The ejector valve was opened slightly permitting a small flow through the equipment. The furnace was lighted and the inlet stagnation chamber temperature was brought up to the desired value. The ejector valve was opened full during this warm-up period and supersonic flow was established in the nozzle. Water injection was begun at the maximum rate desired prior to reaching operating temperature, as steam formation in the injection needles made it difficult to establish flow at low rates with high temperatures. After the temperature had stabilized, pressure and temperature readings were recorded. The water injection rate was then metered down to the next desired value by means of the air pressure regulating valve. Temperature was again stabilized and readings again recorded.

This procedure was continued until five or six flow rates had been recorded including a no-injection run. A lower limit on water injection was established by the instability resulting from steam formation in the needles. The upper limit was determined by the capacity of the air supply. A similar procedure was used for runs at other temperatures, and other positions of water injection. The three injection positions chosen - nozzle entrance, throat, and exit - were determined by the positioning of calibrated marks on the injection tube with respect to the top of the stagnation chamber. The injection tube was secured in position by a lock nut. A detailed drawing of the water injection system is shown in Figure [illegible] of the appendix.

E. Operating Procedure - Subsonic:

The starting procedure was similar to that for supersonic runs. However, in this case, the ejector valve was slowly closed from the open position until it was certain that the flow in the test section was subsonic. The position of the shock in the test section was readily apparent and its motion along the test section and into the nozzle was followed by the fluctuations of the mercury columns on the manometer board. Operation with a Mach no. near one at the throat was extremely unstable and difficult to control by means of the ejector valve. More precise control was obtained through the use of the water spray between the lower stagnation chamber and the ejector tank. This permitted small changes in ejector output by variation in exhaust gas density.

III. RESULTS

All data obtained is tabulated in Tables II - VII of the appendix. Emphasis was placed on obtaining the following information:

a. Effect of inlet temperature on test section pressures for various rates of water injection.

b. Effect of position of injection on test section pressures for various amounts of water injection.

c. Effect of the rate of water injection on test section pressures for given temperature conditions and fixed positions of water injection.

Since the initial test section conditions can be more accurately determined for the case of water injection at the nozzle exit, a comparison of the experimental results with theoretical analysis was made for this condition only, utilizing runs made at an inlet temperature of 1500°R for both the supersonic and subsonic cases. Other runs were compared purely on the basis of experimental results.

Figures III, IV and V show graphically the effect of inlet temperature on end pressure (p_{14}) for various amounts of water injection at supersonic and subsonic flow rates.

Figures VI - X show graphically the effect that water injection position (nozzle entrance, throat, and exit) has on end pressure for various rates of water injection.

Figures III, XI and XVIII show graphically the effect of water injection on static pressure along the test section for injection at the exit of the nozzle for subsonic and supersonic flows.

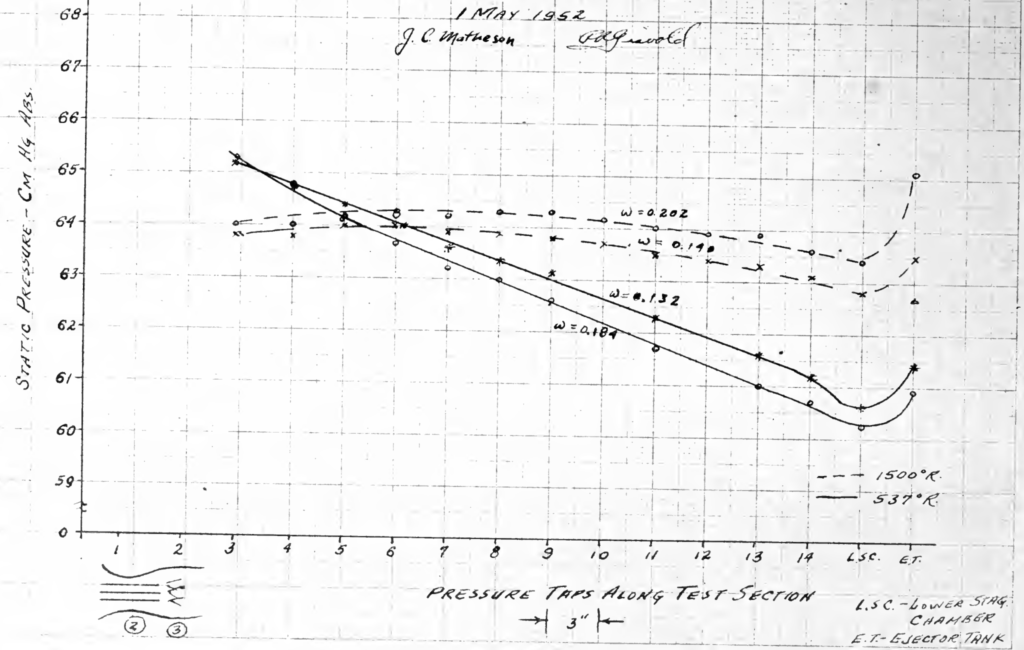
FIGURE III

EFFECT OF WATER INJECTION ON PRESSURE FOR SUBSONIC OPERATION AT 537° AND 1500°R.

INJECTION AT NOZZLE EXIT

1 MAY 1952

J. C. Matheson



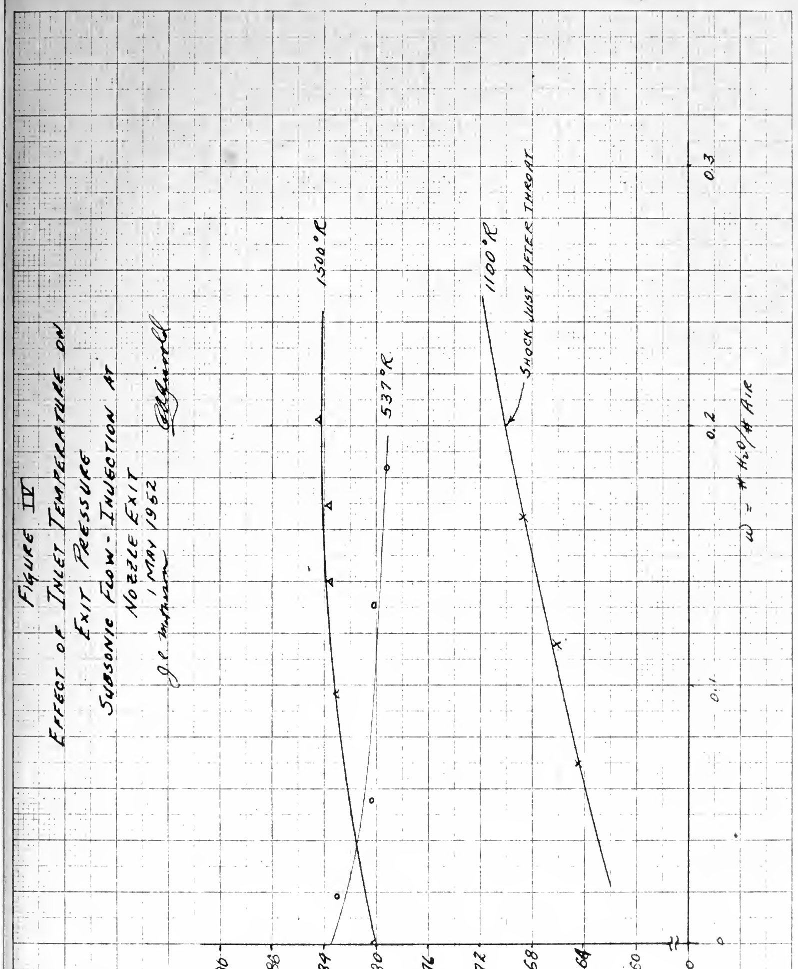


FIGURE IV
EFFECT OF INLET TEMPERATURE ON
EXIT PRESSURE
SUBSONIC FLOW - INJECTION AT
NOZZLE EXIT
1 MAY 1952
1500°R
537°R
1100°R
SHOCK JUST AFTER THROAT
P_{14}/P_1
.90
.88
.84
.80
.76
.72
.68
.64
.60
0
0.1
0.2
0.3
ω = # H_2O/# AIR

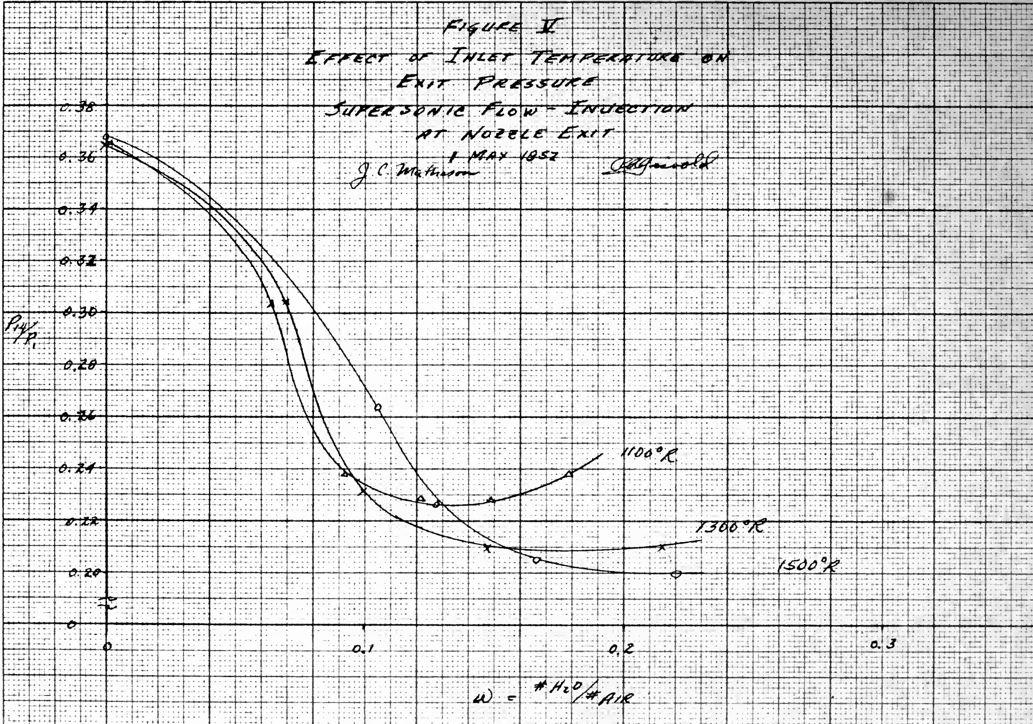


FIGURE V
EFFECT OF INLET TEMPERATURE ON
EXIT PRESSURE
SUPERSONIC FLOW - INJECTION
AT NOZZLE EXIT
1 MAY 1952
J. C. Matheson
0.38
0.36
0.34
0.32
0.30
0.28
0.26
0.24
0.22
0.20
0
P_{14}/P_1
0
0.1
0.2
0.3
1100°R
1300°R
1500°R
$\omega = \#H_2O / \#AIR$

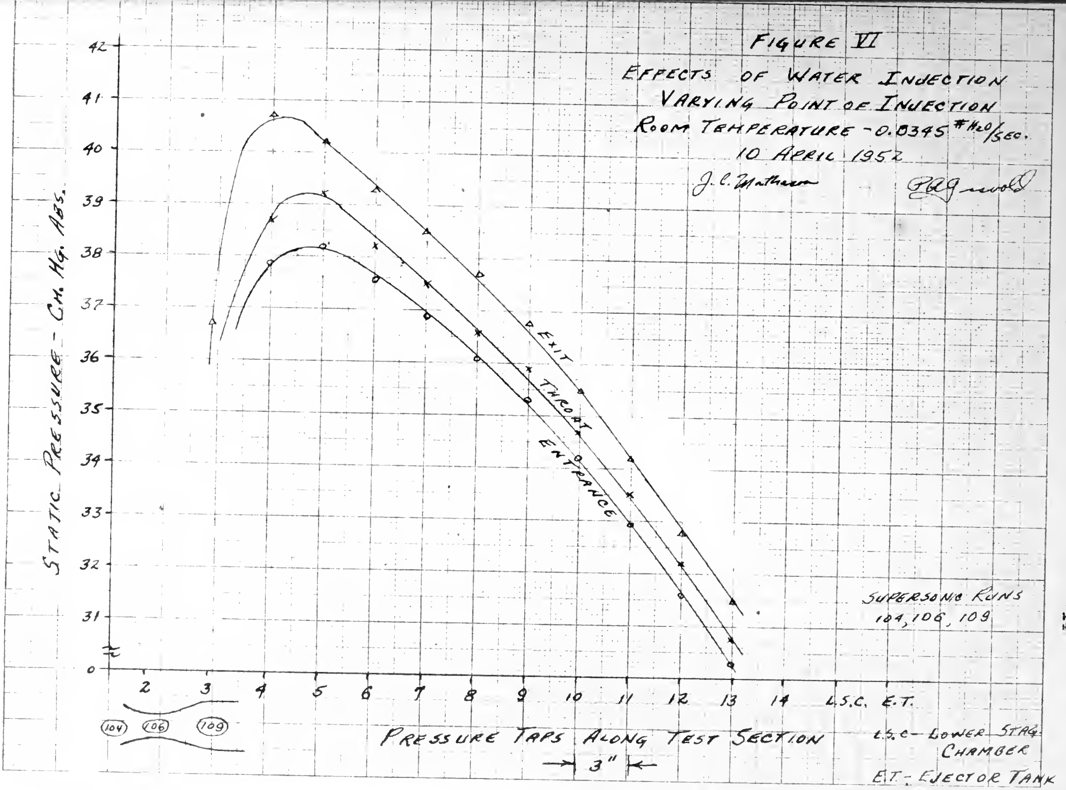


FIGURE VI
EFFECTS OF WATER INJECTION
VARYING POINT OF INJECTION
ROOM TEMPERATURE - 0.0345 # H2O/SEC.
10 APRIL 1952
J. C. Matheson
STATIC PRESSURE - CM. HG. ABS.
42
41
40
39
38
37
36
35
34
33
32
31
0
2
3
4
5
6
7
8
9
10
11
12
13
14
L.S.C.
E.T.
EXIT
THROAT
ENTRANCE
104
106
109
PRESSURE TAPS ALONG TEST SECTION
3"
SUPERSONIC RUNS
104, 106, 109
L.S.C - LOWER STAG CHAMBER
E.T. - EJECTOR TANK

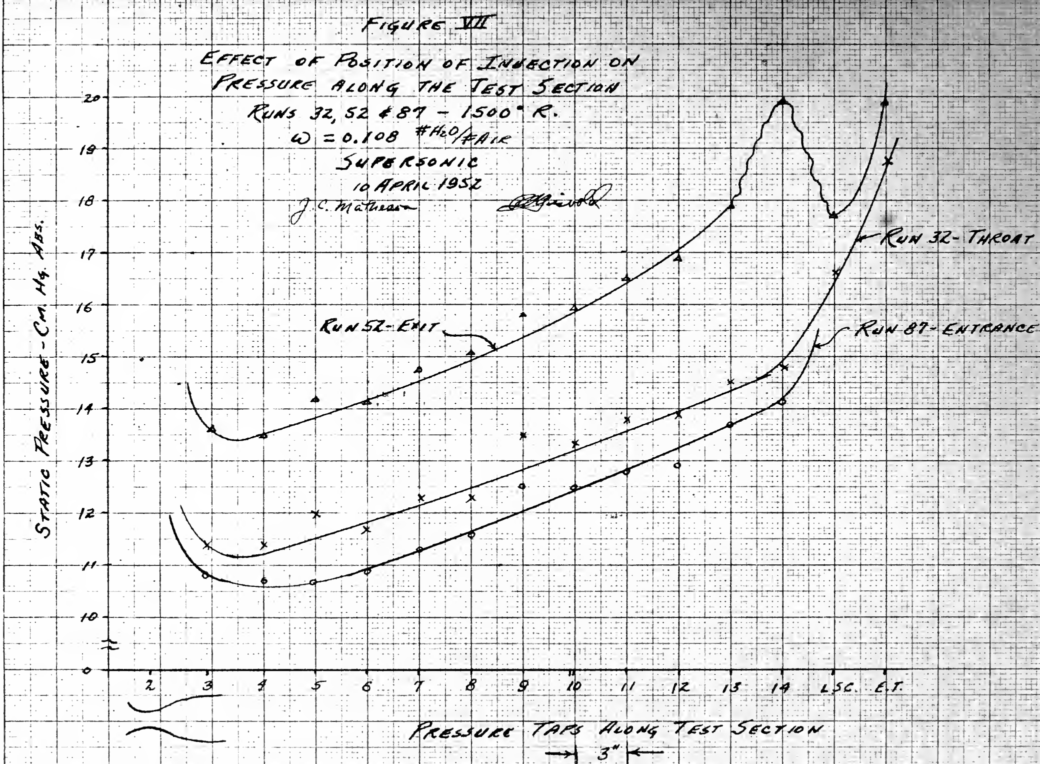


FIGURE VII
EFFECT OF POSITION OF INJECTION ON PRESSURE ALONG THE TEST SECTION
RUNS 32, 52 & 87 - 1500° R.
ω = 0.108 #H2O/#AIR
SUPERSONIC
10 APRIL 1952
J. C. Matheson
RUN 52-EXIT
RUN 32-THROAT
RUN 87-ENTRANCE
STATIC PRESSURE - CM. HG. ABS.
20
19
18
17
16
15
14
13
12
11
10
0
2
3
4
5
6
7
8
9
10
11
12
13
14
LSC.
E.T.
PRESSURE TAPS ALONG TEST SECTION
3"

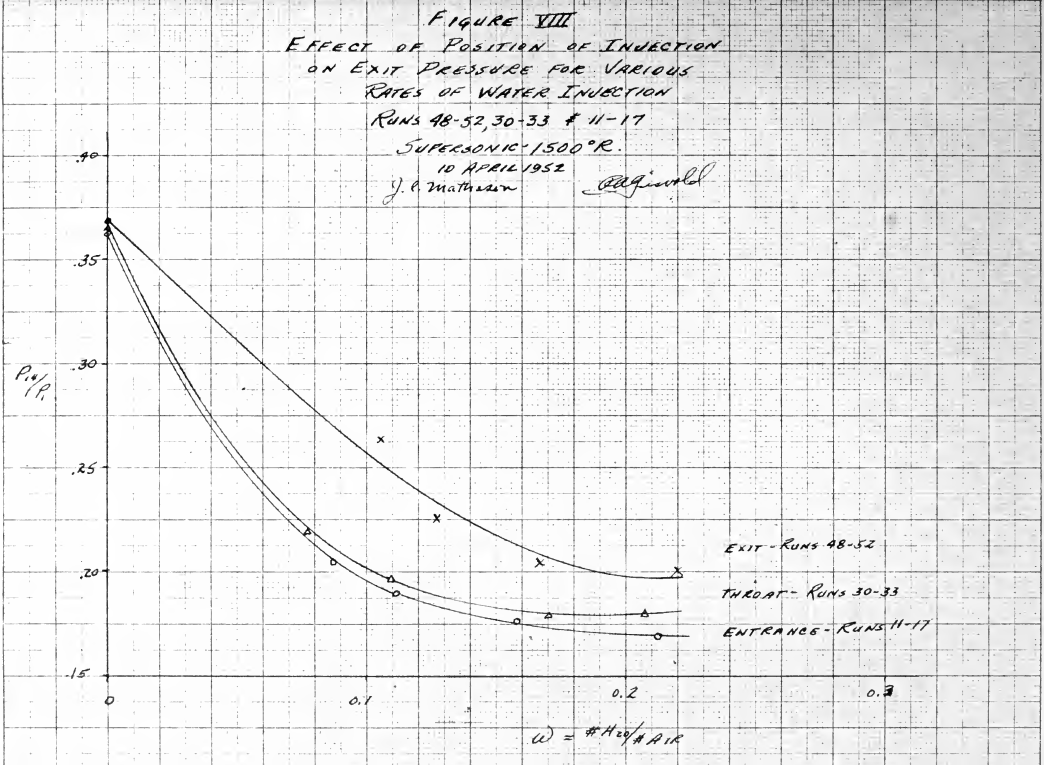
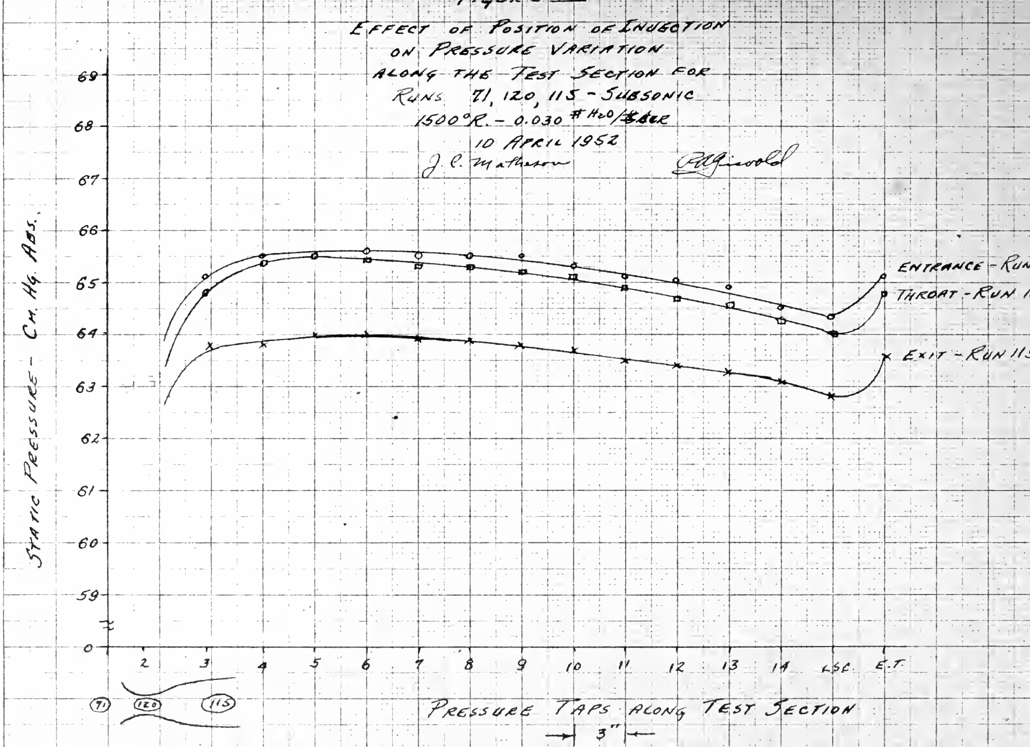


FIGURE VIII
EFFECT OF POSITION OF INJECTION
ON EXIT PRESSURE FOR VARIOUS
RATES OF WATER INJECTION
RUNS 48-52, 30-33 & 11-17
SUPERSONIC-1500°R.
10 APRIL 1952
J. C. Matheson
.40
.35
.30
.25
.20
.15
P_{14}/P_1
EXIT - RUNS 48-52
THROAT - RUNS 30-33
ENTRANCE - RUNS 11-17
0
0.1
0.2
0.3
ω = # H_2O/# AIR


EFFECT OF POSITION OF INJECTION
ON PRESSURE VARIATION
ALONG THE TEST SECTION FOR
RUNS 71, 120, 115 - SUBSONIC
1500°R. - 0.030 # H2O/# AIR
10 APRIL 1952
J. C. Matheson
ENTRANCE - RUN 71
THROAT - RUN 120
EXIT - RUN 115
STATIC PRESSURE - CM. HG. ABS.
69
68
67
66
65
64
63
62
61
60
59
0
2
3
4
5
6
7
8
9
10
11
12
13
14
LSC.
E.T.
71
120
115
PRESSURE TAPS ALONG TEST SECTION
3"

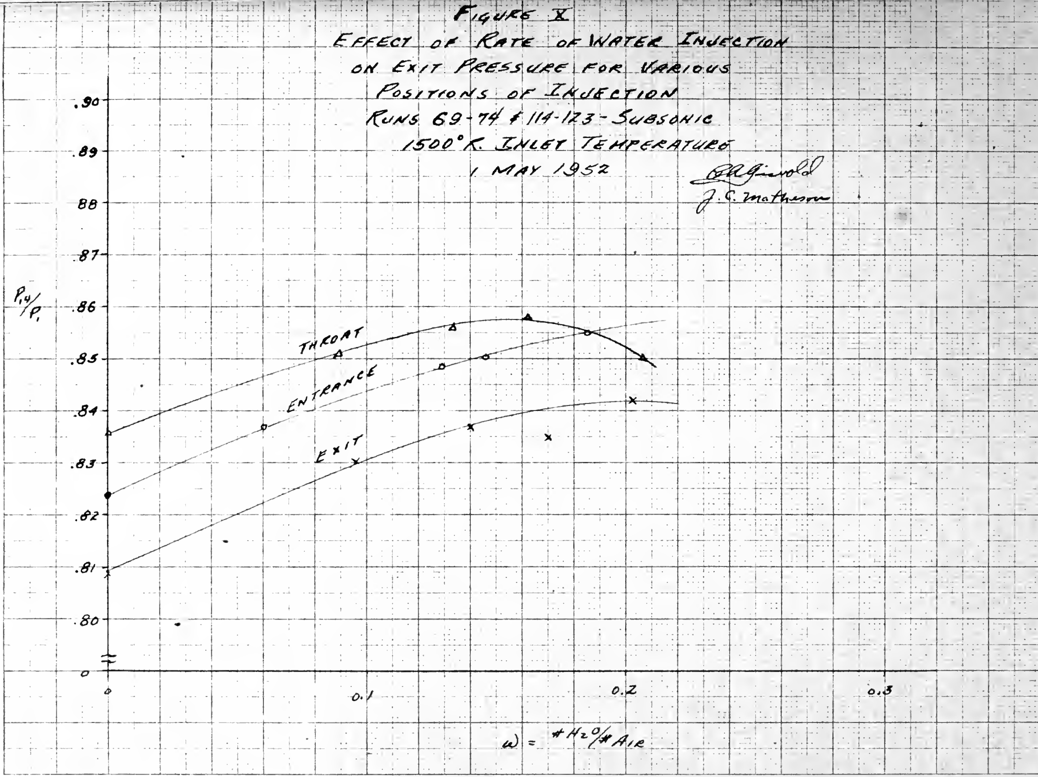


FIGURE X
EFFECT OF RATE OF WATER INJECTION
ON EXIT PRESSURE FOR VARIOUS
POSITIONS OF INJECTION
RUNS 69-74 & 114-123 - SUBSONIC
1500°R. INLET TEMPERATURE
1 MAY 1952

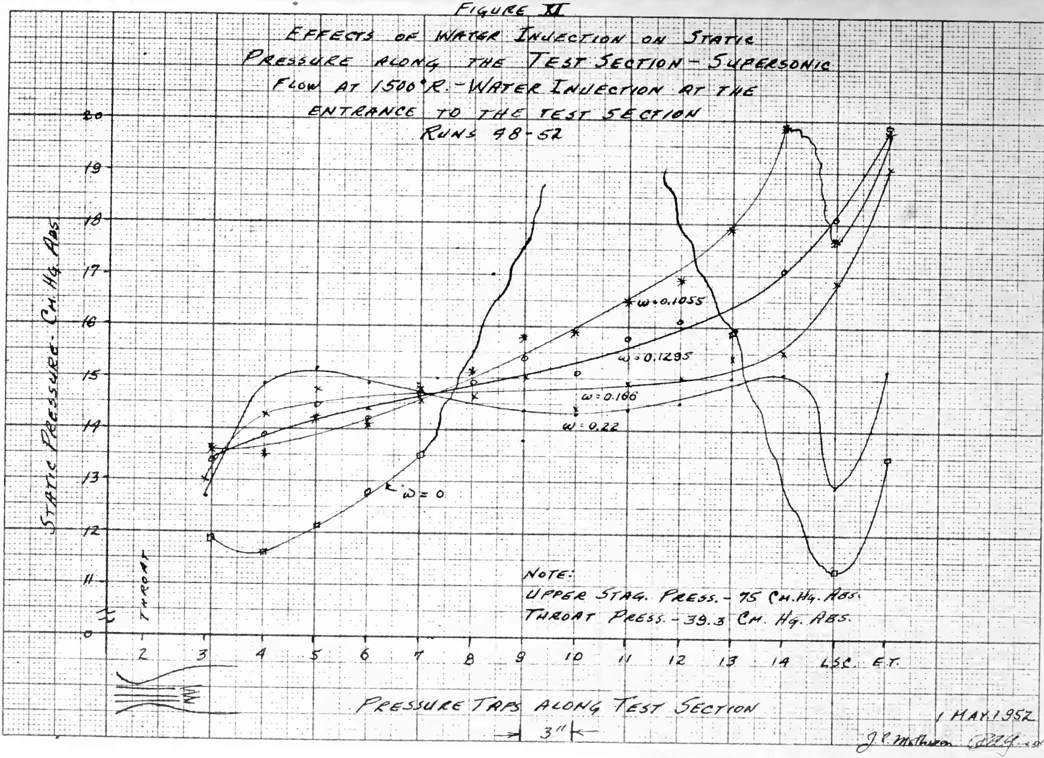


FIGURE XI
EFFECTS OF WATER INJECTION ON STATIC PRESSURE ALONG THE TEST SECTION - SUPERSONIC FLOW AT 1500°R. - WATER INJECTION AT THE ENTRANCE TO THE TEST SECTION
RUNS 48-52
STATIC PRESSURE - CM. HG ABS
20
19
18
17
16
15
14
13
12
11
0
THROAT
2
3
4
5
6
7
8
9
10
11
12
13
14
LSC
E.T.
ω = 0.1055
ω = 0.1295
ω = 0.166
ω = 0.22
ω = 0
NOTE:
UPPER STAG. PRESS. - 75 CM. HG. ABS.
THROAT PRESS. - 39.3 CM. HG. ABS.
PRESSURE TAPS ALONG TEST SECTION
3"
1 MAY 1952

Test runs number 99 through 113 were made at room temperature in an effort to determine the friction effect at various rates of water injection for unevaporated water. This information for the subsonic case - injection at nozzle exit - is plotted in Figure III. The results in the supersonic case were largely indeterminate in that the friction at even small injection rates produced choking effect in the test section. The friction factor determined from the high temperature dry runs was an approximation to the friction factor under complete evaporation. The friction factors determined from these dry runs with the injection needles at the nozzle exit are as follows:

Run	Mach No.	T_{o1}	f
48	1.80	1500°R.	0.0030
118	0.382	1500°R.	0.0048

Shocks in the test section were easily identified when present and are indicated with an asterisk in the tabulated data. A shock was present in the test section at approximately mid-length in all dry supersonic runs, however, in the high temperature runs it disappeared upon the injection of but small amounts of water. The initial Mach numbers obtained in the supersonic dry runs varied from 1.80 with injection needles at the nozzle exit to 1.95 with needles at the nozzle entrance. Those of the subsonic runs varied from 0.382 to 0.392. An effort was made in all subsonic runs to keep the Mach number at the throat as near one as possible.

Impact tube readings for both supersonic and subsonic runs made it apparent that the lower stagnation chamber was acting more as a diffuser than as a stagnation chamber. Thus

the ejector tank pressure was used as the best indication of exit stagnation pressure. Due to the ineffectiveness of the lower stagnation chamber all supersonic runs except 86 through 98 were made with the air ejector valve wide open. In the case of runs 86 through 98 an effort was made to maintain the shock at the test section exit.

IV. DISCUSSION OF RESULTS

A. Criterion of Aerothermopressor Effectiveness:

The overall effectiveness of the aerothermopressor is indicated by the ratio of exit stagnation pressure to inlet stagnation pressure. Since the experimental equipment failed to provide reliable lower stagnation chamber readings, effectiveness can be compared only on the basis of static pressure variation in the test section. Since in a supersonic stream, friction is known to increase the static pressure and cooling reduce it, the lowest ratio of exit to inlet static pressure is the measure of greatest effectiveness. In subsonic flow, the highest ratio of exit to inlet static pressure indicates greatest effectiveness. Where plotted this ratio is expressed as the ratio of test section exit pressure to nozzle inlet pressure (P_{14}/P_1). Since test section inlet pressure w s found to vary somewhat with injection rate and injection position, the relatively constant nozzle inlet pressure provided the better reference.

B. Inlet Temperature Influence:

Figure III indicates the variation of test section pressure with length for various rates of injection at room temperature and 1500°R. for subsonic flow. The curves show clearly the effect of evaporation in raising the downstream static pressure. The positive slope in the upstream part of the test section presumably represents a greater rate of evaporation per unit length than in the downstream region. It is noted that while drag effects at room temperatures are increased with increased rates of injection, at 1500°R. they

are reduced with increased injection.

Figure IV expresses the variation of pressure ratio with injection rate at various temperatures for the subsonic case. The advantage of 1500°R. is apparent by higher p_{14}/p_1 ratios. The apparent disadvantage of the 1100°R. data is explained by the suspected presence of a shock between the nozzle throat and exit, resulting in appreciably higher Mach number at the test section entrance. Figure X demonstrates the effect of injection rate on pressure ratio for the supersonic case at various inlet temperatures. The greatest net effectiveness is seen in the 1500°R. run. Since the amount of water for saturation increases with increased temperature, the apparent reversal of slope in the respective runs indicate possible saturation in the 1100°R. and 1300°R. runs. The greater effectiveness of the 1100°R. run at low injection rates suggests that time required for evaporation is more important than temperature differential. A lower velocity is associated with the lower temperature run at approximately constant Mach number along the test section.

C. Position of Injection Influence:

Desirable injection features were thought to include minimum drop size, maximum dispersion throughout the gas stream and minimum acceleration drag. Three positions of injection - nozzle entrance, nozzle throat, and nozzle exit - were selected for obtaining data and for analysis. For the supersonic case, the nozzle entrance injection was used for minimum relative velocity, the nozzle throat for minimum stream area, and the nozzle exit for maximum relative velocity and ease of theoretical analysis. For the subsonic case, the

nozzle entrance injection was used for minimum relative velocity, nozzle throat for minimum stream area and maximum relative velocity, and nozzle exit for theoretical analysis.

Figures VII and VIII illustrate the effect of injection position on pressure for the supersonic case at 1500°R. The variation of pressure with length at constant injection rate and with injection at entrance, throat and exit is illustrated in Figure VII. Figure VIII represents the effect on pressure ratio at various injection rates of the three positions of injection. The apparent advantage of the entrance injection position may be due to the fact that a higher Mach number existed at the nozzle exit for this case. This advantage is particularly apparent in comparing throat and entrance curves with the exit curve of Figure VII.

Figures IX and X indicate the effect of injection position on pressure for subsonic flow at 1500°R. Figure IX illustrating variation of pressure with length indicating an apparent advantage for the entrance position of injection. This may be due to a difference in nozzle exit Mach number. Figure X depicting variation of pressure ratio with injection rate indicates an advantage for throat or entrance injection over exit injection for the region investigated.

D. <u>Rate of Water Injection Influence:</u>

The variation of pressure with injection rate for the subsonic case is best observed in Figures IV, X, and XVIII. In general, the effectiveness is seen to increase with increase in injection rate. It is expected that such increase would continue to a point of stream saturation. In the subsonic runs the capacity limit of the injection system prevented sufficient data at higher injection rates to accurately

predict a saturation point. The inflections in the throat and exit curves of Figure X possibly indicate points of saturation.

The variation of pressure with injection rate for supersonic flow is best seen in Figures V, VIII, and XI. Again effectiveness is seen to increase with rate of injection. Except for the 1100°R. run of Figure V, stream saturation is not indicated in these curves.

E. Analysis of Data With Respect to Theory

1. Introduction: An effort was made to predict theoretically the operation of the constant area aerothermopressor in terms of exit pressures, temperatures and Mach number for given initial conditions. The method chosen was the analysis of a discontinuity using the control surface technique suggested by Shapiro and Hawthorne(1). For purposes of analysis the following assumptions were made: Flow adiabatic, liquid injection velocity zero and wall friction present. Appendix C contains the derivation of the working equations employed. The analysis was divided into two sections. The first assumed complete evaporation at the test section exit. Calculations were made for test section exit conditions using values of injection rate from zero to the amount necessary for saturation at the exit temperature. These were carried out for the subsonic and supersonic cases over a range of friction factors from zero to twice the dry run value. Initial conditions were determined from dry run nozzle exit conditions at 1500°R. and with exit injection (runs #48 and #118). These values are included in Appendix C. The calculations were plotted as exit pressure, temperature and Mach number vs. rate of injection and compared to the experimental results of runs with similar inlet conditions.

The second method assumed incomplete evaporation of the liquid injected. The results of this calculation were plotted as exit static pressure vs. percent evaporation for a particular rate of injection. These calculations were made over a range of friction factors for the subsonic and supersonic

cases. It was hoped from this latter analysis to determine from the test section static pressure readings and reasonably reliable friction data, an indication of the amount and history of the evaporation in a particular run.

2. Analysis of Supersonic Runs: Runs #48-52 were made with an inlet stagnation temperature of 1500°F. and water injection at the nozzle exit. Figure XI illustrates the variation of pressure with length for the injection rates measured. The location of the shock in the dry run is indicated by the pressure discontinuity. It is noted that the nozzle exit Mach number is somewhat less for the wet runs than for the dry. The inflection point noted in the upstream part of the test section for the high injection rate runs, is interpreted as an indication of higher acceleration drag at high ratè of injection.

Figures XII thru XV show calculated test section exit conditions plotted vs. injection rate (complete evaporation assumed) for the initial conditions of run #48. On these figures have been plotted the experimental points obtained from runs of similar initial conditions. The limits of the calculated curves are injection rate equivalent to saturation, and minimum injection rate necessary for shock-free flow in the test section. This latter figure is seen to increase with increased friction factor (expressed in terms of fL/D). Figure XII expresses the comparison of calculated and experimental exit temperatures. As in the case of pressure, the temperature readings of the lower stagnation chamber do not reflect stagnation conditions, nor are they equivalent to the exit static temperature obtained from calculation. Thus, their

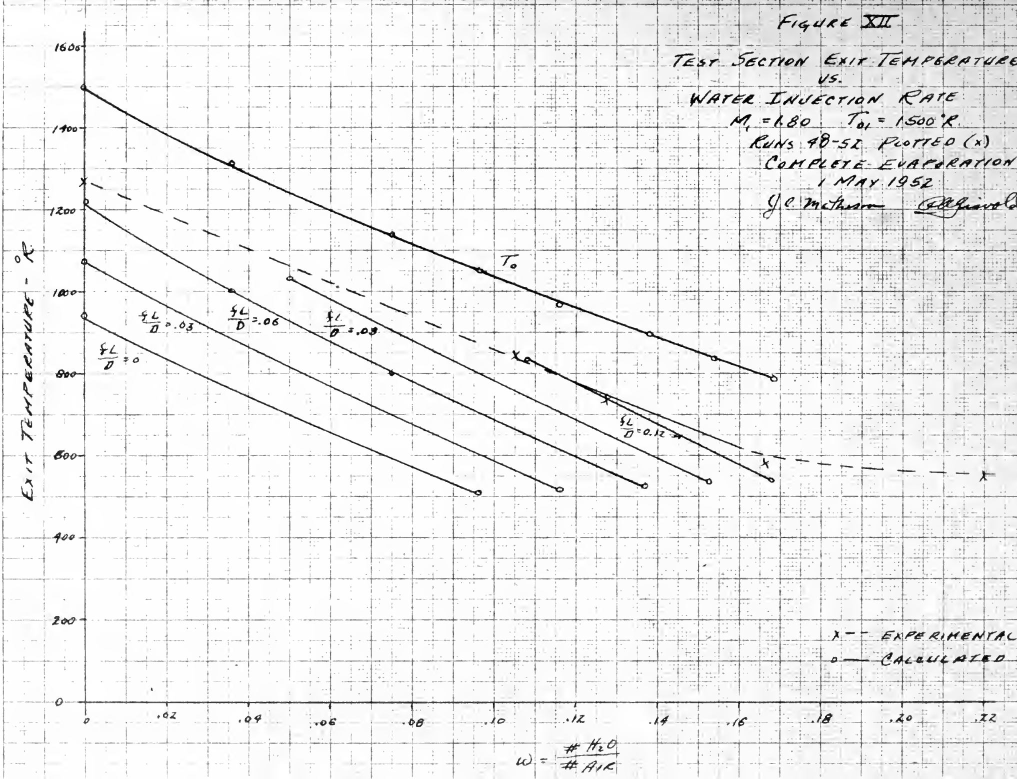


FIGURE XII
TEST SECTION EXIT TEMPERATURE
VS.
WATER INJECTION RATE
$M_1 = 1.80$ $T_{01} = 1500°R$
RUNS 48-52 PLOTTED (x)
COMPLETE EVAPORATION
1 MAY 1952
J C McKissen
x - - EXPERIMENTAL
o —— CALCULATED
EXIT TEMPERATURE - °R
1600
1400
1200
1000
800
600
400
200
0
.02
.04
.06
.08
.10
.12
.14
.16
.18
.20
.22
$\omega = \frac{\# H_2O}{\# AIR}$
T_0
$\frac{fL}{D} = 0$
$\frac{fL}{D} = .03$
$\frac{fL}{D} = .06$
$\frac{fL}{D} = .09$
$\frac{fL}{D} = 0.12$

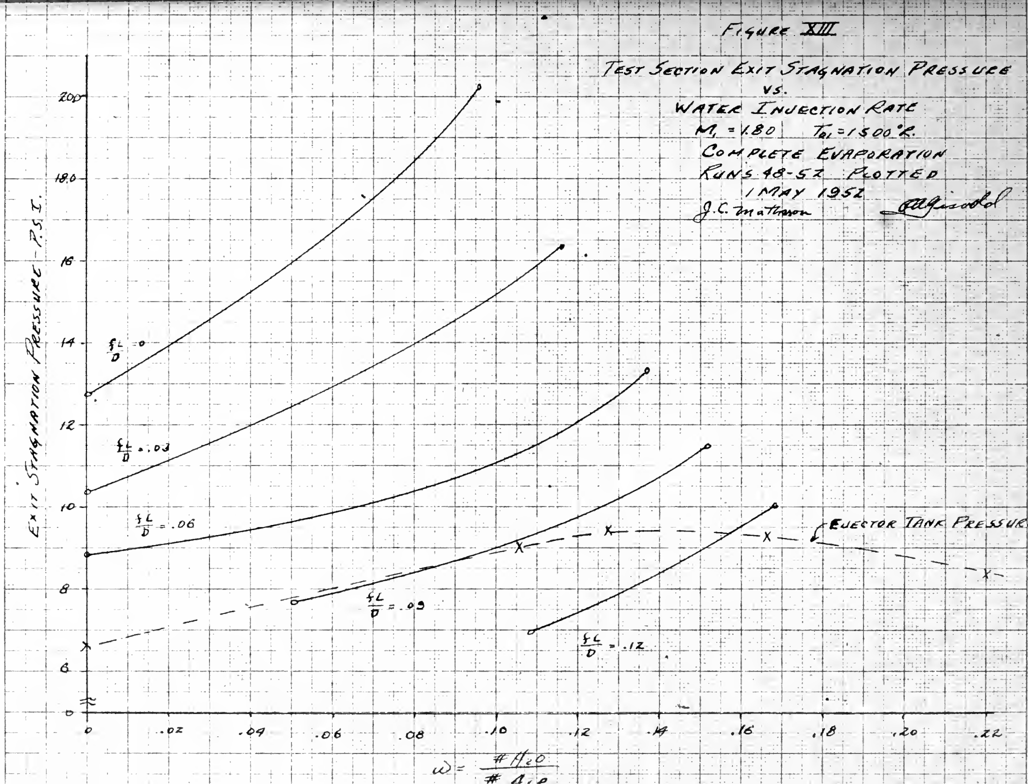


FIGURE XIII
TEST SECTION EXIT STAGNATION PRESSURE
VS.
WATER INJECTION RATE
$M_1 = 1.80$ $T_{01} = 1500°R$.
COMPLETE EVAPORATION
RUNS 48-57 PLOTTED
1 MAY 1952
J.C. Mathason
EXIT STAGNATION PRESSURE - P.S.I.
$\frac{fL}{D} = 0$
$\frac{fL}{D} = .03$
$\frac{fL}{D} = .06$
$\frac{fL}{D} = .09$
$\frac{fL}{D} = .12$
EJECTOR TANK PRESSURE
$\omega = \frac{\# H_2O}{\# AIR}$
0
.02
.04
.06
.08
.10
.12
.14
.16
.18
.20
.22
6
8
10
12
14
16
18.0
20.0

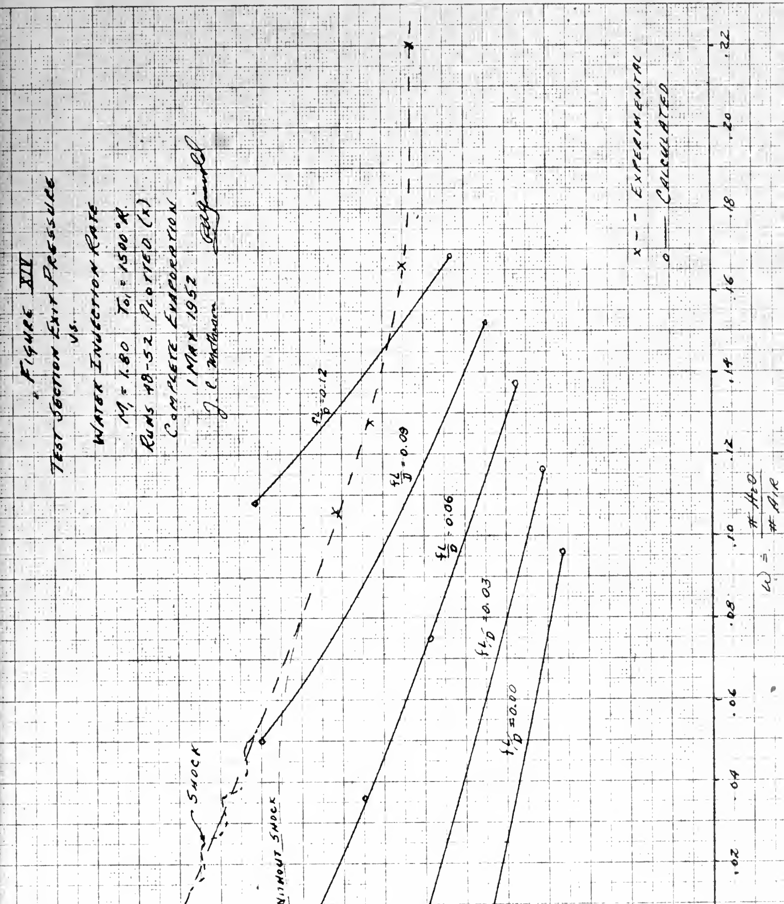


FIGURE XIV
TEST SECTION EXIT PRESSURE
vs.
WATER INJECTION RATE
$M_1 = 1.80$ $T_{01} = 1500°R$
RUNS 48-52 PLOTTED (x)
COMPLETE EVAPORATION
1 MAY 1952
$\frac{fL}{D} = 0.12$
$\frac{fL}{D} = 0.09$
$\frac{fL}{D} = 0.06$
$\frac{fL}{D} = 0.03$
$\frac{fL}{D} = 0.00$
SHOCK
WITHOUT SHOCK
x - - EXPERIMENTAL
o —— CALCULATED
EXIT PRESSURE - PSI
6.0
5.0
4.0
3.0
2.0
1.0
0
0
.02
.04
.06
.08
.10
.12
.14
.16
.18
.20
.22
$\omega = \frac{\# H_2O}{\# AIR}$

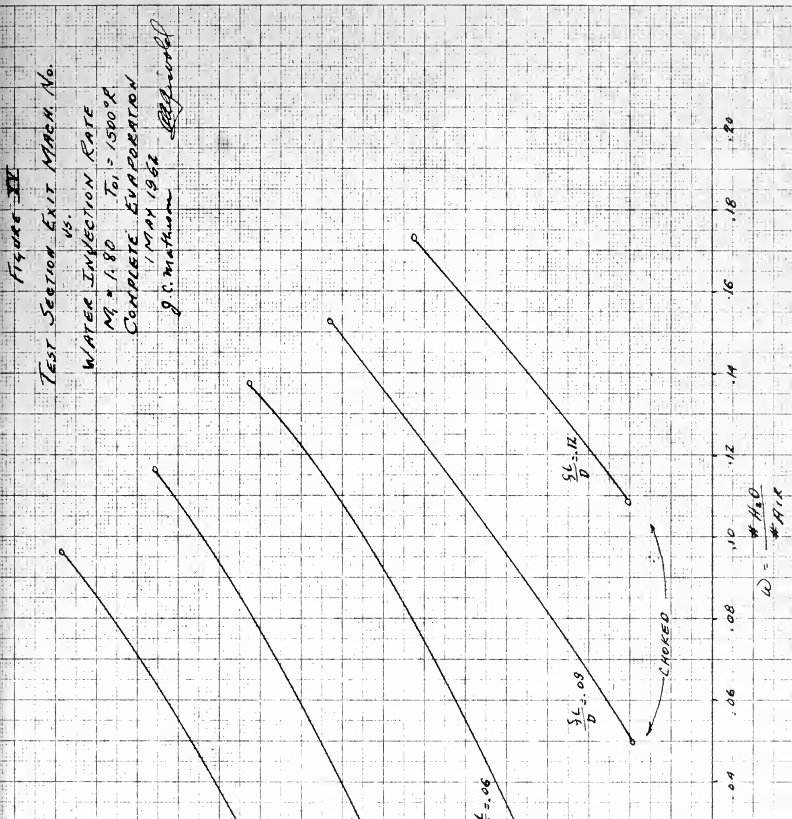


Figure XV
Test Section Exit Mach No.
vs.
Water Injection Rate
M1 = 1.80 T01 = 1500°R
Complete Evaporation
1 May 1962
J.C. Mathews
fL/D = 0
fL/D = .03
fL/D = .06
fL/D = .09
fL/D = .12
CHOKED
Exit Mach No.
2.4
2.2
2.0
1.8
1.6
1.4
1.2
1.0
0
.02
.04
.06
.08
.10
.12
.14
.16
.18
.20
ω = #H2O / #AIR

configuration rather than magnitude is significant. The relatively constant temperature obtained for rates of injection in excess of those predicted for saturation suggest that saturation has been reached.

Figure XIII depicts calculated test section exit stagnation pressure. The plotted experimental points represent ejector tank pressure. These values, though a better measure of stagnation pressure than obtained from the lower stagnation chamber, are less than test section exit stagnation pressure by the pressure drop due to shock and piping losses. Thus, again the shape rather than magnitude is significant. The maximum indicated in the region of $\omega = 0.14$ suggests saturation at this point. The effect of injection at rates in excess of the amount that can be evaporated is increased drag manifest by a decrease in pressure.

Figure XIV illustrates calculated and measured test section exit pressures. Again the measured values indicate an approach to saturation at high values of water injection. The presence of shock in the test section and absence of data at low water injection rates gives little information for that portion of the curve. However, over the range of measured data, the points fall along a line of increasing friction factor. This configuration would indicate an increase in friction with increased injection rates. Contributing also, is the strong possibility of only partial evaporation of the water injected.

Figure XV shows the variation in test section exit Mach number with injection rate. Although experimental results appear to substantiate the increase in Mach number with injection rate, the lack of reliable exit stagnation temperature or

pressure data made it impossible to determine an accurate experimental exit Mach number.

Figure XVI depicts calculated curves of test section exit pressure vs. percent of water evaporated for an injection rate of $\omega = 0.1055$. It is noted that this injection rate is considerably less than the amount predicted for saturation at anticipated friction factors. The analysis of complete evaporation indicated a variation in friction factor with rate of injection. This was borne out by estimates of the friction factor made for room temperature subsonic runs at various injection rates (see Fig. XXVII). It was further found that the friction factor in the room temperature runs was of the order of twice the 1500°R. dry run value. As the friction factors computed for dry runs at room temperature were similar to those computed for dry runs at 1500°R., it was assumed that the room temperature wet run friction factor was a reasonable approximation to the friction factor due to unevaporated water at 1500°R.

It was assumed that the mean friction factor for a particular run would lie somewhere between the dry run value and that of unevaporated water at that temperature. Unfortunately, it was not possible to obtain estimates of the room temperature friction factor with water injection for supersonic runs, inasmuch as the introduct on of but negligible amounts of water produced a choking effect resulting in subsonic flow throughout the test section (Fig. VI shows this effect). Thus for the supersonic case, the mean friction factor was arbitrarily assumed 50% greater than the dry run value. This

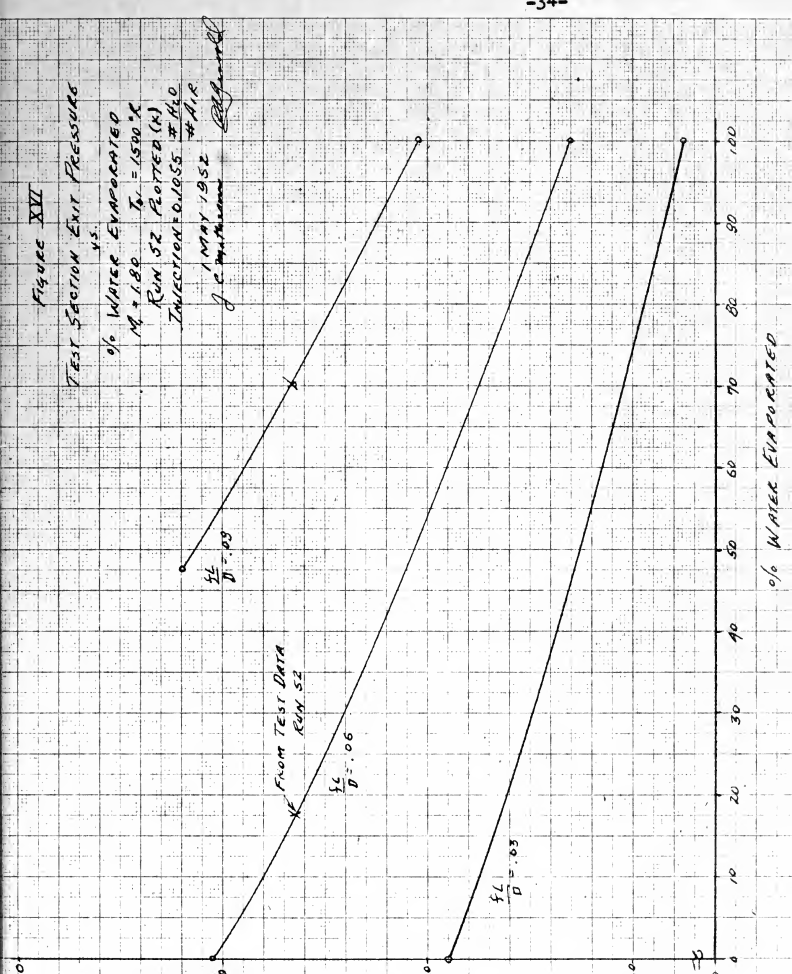


FIGURE XVII
TEST SECTION EXIT PRESSURE
vs.
% WATER EVAPORATED
M1 = 1.80   T01 = 1500°R
RUN 52 PLOTTED (X)
INJECTION = 0.1055 #H2O / #AIR
1 MAY 1952
fL/D = .09
fL/D = .06
fL/D = .03
FROM TEST DATA RUN 52
0
10
20
30
40
50
60
70
80
90
100
% WATER EVAPORATED
2.0
3.0
4.0
5.0
EXIT PRESSURE - PSI.

is equivalent to an fL/D of 0.09. The measured exit pressure for run #52 has been plotted as a point on the curve of fL/D=0.09. This indicates evaporation of 70% of the water injected for that run. It is apparent that had the mean friction factor been greater, a greater percentage of evaporation could be expected. Figure XVII represents the variation of percent evaporation over length of test section. This curve was obtained from the measured values of pressure along the test section for run #52, an assumed mean friction factor, and Figure XVI. The variation of evaporation with length suggests that for the supersonic case the maximum rate of evaporation is not reached until approximately the middle of the test section, or following the initial acceleration. This may be attributed to relatively greater time for evaporation in the downstream section, as the theoretical calculations indicate a decrease in velocity from the test section inlet to exit. However, the lack of more precise friction information introduces a serious uncertainty.

3. Analysis of Subsonic Runs: Runs #114-118 were made with an inlet stagnation temperature of 1500°R. and water injection at the nozzle exit. Figure XVIII illustrates the variation of pressure with length for the injection rates measured. It is noted that the nozzle exit Mach number is somewhat greater for the wet runs than for the dry runs.

Figures XIX-XXII show calculated test section exit conditions plotted vs. injection rate (complete evaporation assumed) for the initial conditions of run #118. On these figures have been plotted the experimental points obtained from runs of similar initial conditions. It is pointed out

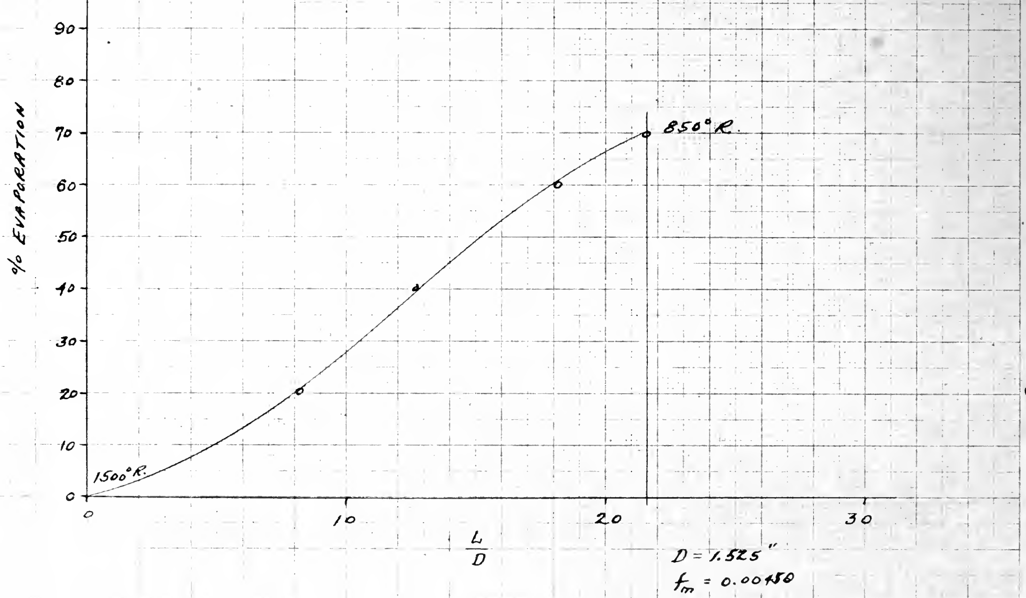
FIGURE XVII

% EVAPORATION VS. L/D BASED ON A MEAN FRICTION FACTOR; $f_m = 0.00416$

RUN 52 PLOTTED — $\omega = 0.1055$ #H_2O/#AIR

SUPERSONIC

J.C. McThem 1 MAY 1952



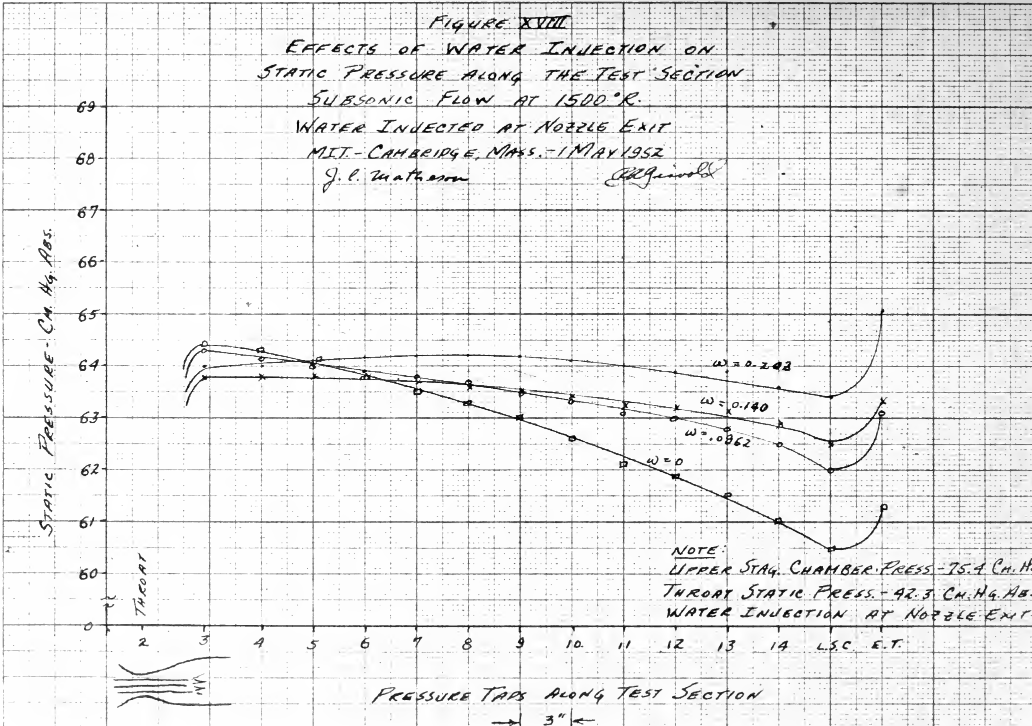


FIGURE XVIII
EFFECTS OF WATER INJECTION ON
STATIC PRESSURE ALONG THE TEST SECTION
SUBSONIC FLOW AT 1500°R.
WATER INJECTED AT NOZZLE EXIT
MIT - CAMBRIDGE, MASS. - 1 MAY 1952
J. L. Matheson
ω = 0.203
ω = 0.140
ω = .0862
ω = 0
NOTE:
UPPER STAG. CHAMBER PRESS. - 75.4 CM. HG. ABS.
THROAT STATIC PRESS. - 42.3 CM. HG. ABS.
WATER INJECTION AT NOZZLE EXIT
STATIC PRESSURE - CM. HG. ABS.
69
68
67
66
65
64
63
62
61
60
0
THROAT
2
3
4
5
6
7
8
9
10
11
12
13
14
L.S.C.
E.T.
PRESSURE TAPS ALONG TEST SECTION
3"

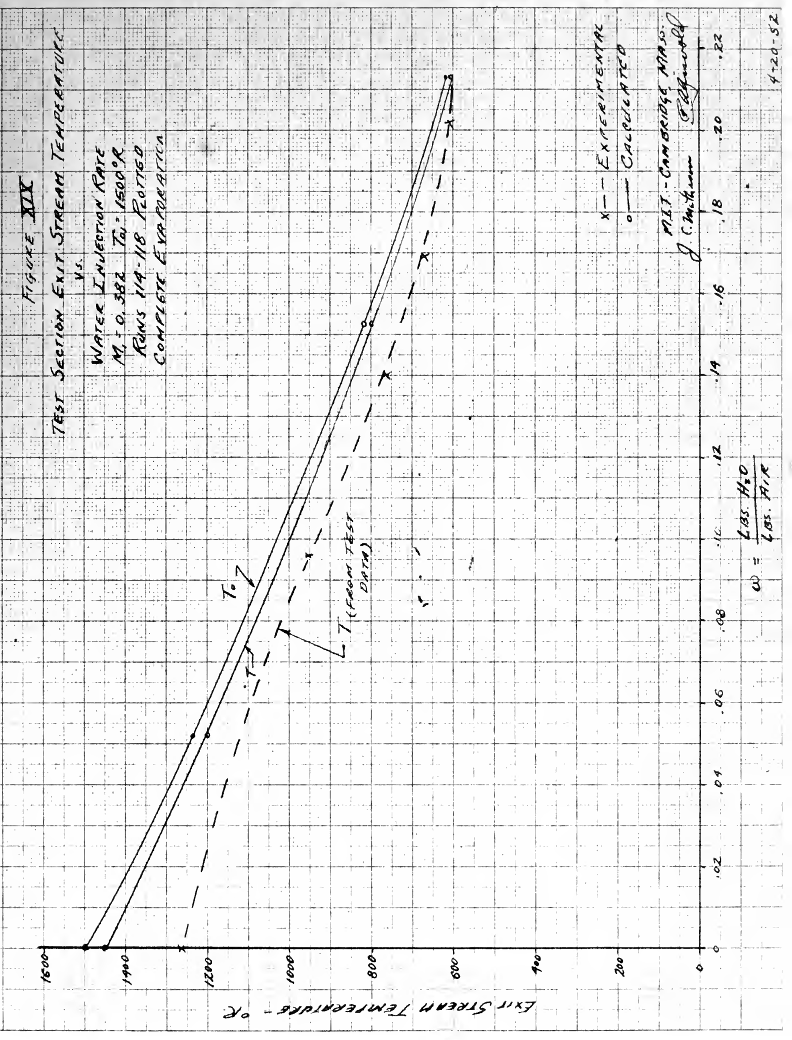


FIGURE XIX
TEST SECTION EXIT STREAM TEMPERATURE
VS.
WATER INJECTION RATE
M₁ = 0.382 T₀₁ = 1500°R
RUNS 114-118 PLOTTED
COMPLETE EVAPORATION
T₀
T
T (FROM TEST DATA)
x - - EXPERIMENTAL
o —— CALCULATED
M.I.T. - CAMBRIDGE, MASS.
J. C. Mitchum
4-20-52
EXIT STREAM TEMPERATURE - °R
1600
1400
1200
1000
800
600
400
200
0
.02
.04
.06
.08
.10
.12
.14
.16
.18
.20
.22
ω = LBS. H₂O / LBS. AIR

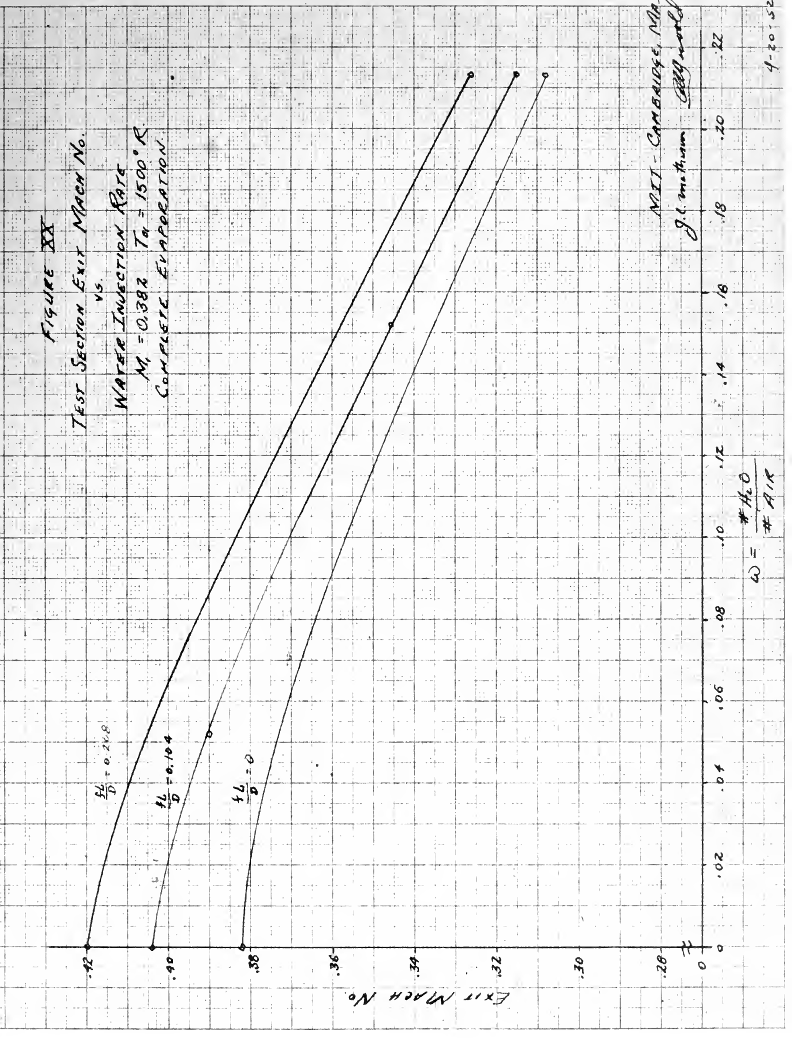


FIGURE XX
TEST SECTION EXIT MACH NO.
VS.
WATER INJECTION RATE
$M_1 = 0.382$ $T_{a} = 1500°R$.
COMPLETE EVAPORATION.
MIT - CAMBRIDGE, MASS
J.C. Witham
4-20-52
$\frac{fL}{D} = 0.208$
$\frac{fL}{D} = 0.104$
$\frac{fL}{D} = 0$
EXIT MACH NO.
.42
.40
.38
.36
.34
.32
.30
.28
0
.02
.04
.06
.08
.10
.12
.14
.16
.18
.20
.22
$\omega = \frac{\# H_2O}{\# AIR}$

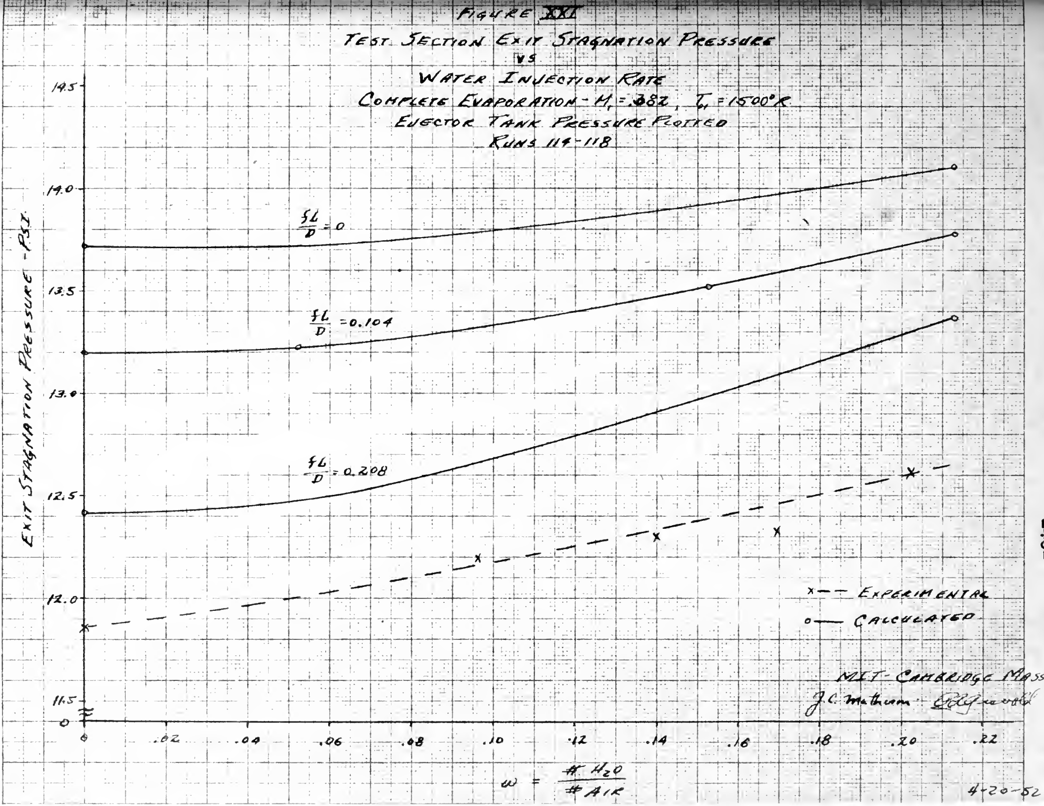


FIGURE XXI
TEST SECTION EXIT STAGNATION PRESSURE
VS
WATER INJECTION RATE
COMPLETE EVAPORATION - $M_1 = .382$, $T_1 = 1500°R$
EJECTOR TANK PRESSURE PLOTTED
RUNS 114-118

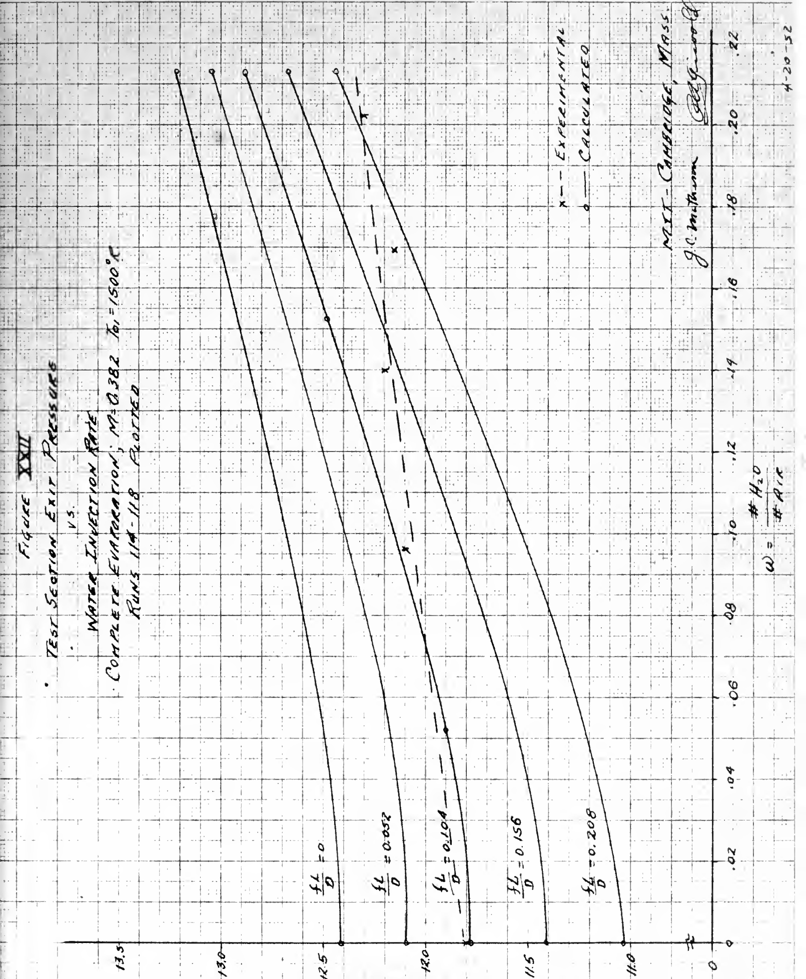


FIGURE XXII
TEST SECTION EXIT PRESSURE vs. WATER INJECTION RATE
COMPLETE EVAPORATION; $M_1 = 0.382$ $T_{01} = 1500°R$
RUNS 114-118 PLOTTED

that in the subsonic case there is no noticeable change in the amount of water necessary for saturation at different friction factors. Figure XIX depicts calculated and measured test section exit temperatures. Variation in friction factor over the range calculated had no appreciable effect on exit static temperature. The difference in stagnation and static temperature is seen to be slight for relatively low Mach numbers. It is noted that for the same inlet stagnation temperatures, the exit and mean test section static temperature is higher than for the supersonic case. This results in a greater rate of injection for saturation in the subsonic case, as well as a greater temperature difference between hot gas and injection water. The deviation of measured temperature from predicted values is believed due to radiation losses from the thermocouple in the lower stagnation chamber. The close agreement at low temperature and increasing lack of agreement at higher temperatures supports this contention. Although the upper thermocouple was believed to be effectively shielded, radiation losses in the upper stagnation chamber admit the possibility of a somewhat higher inlet stagnation temperature than measured.

Figure XX illustrates the variation of exit Mach number with injection rate obtained from calculation. The Mach number is seen to decrease with increased injection for the case of subsonic flow. Though this decrease was evident from measured data, lack of sufficiently reliable temperature and pressure data precluded accurate determination of experimental exit Mach number values.

Figure XXI depicts the calculated variation of test

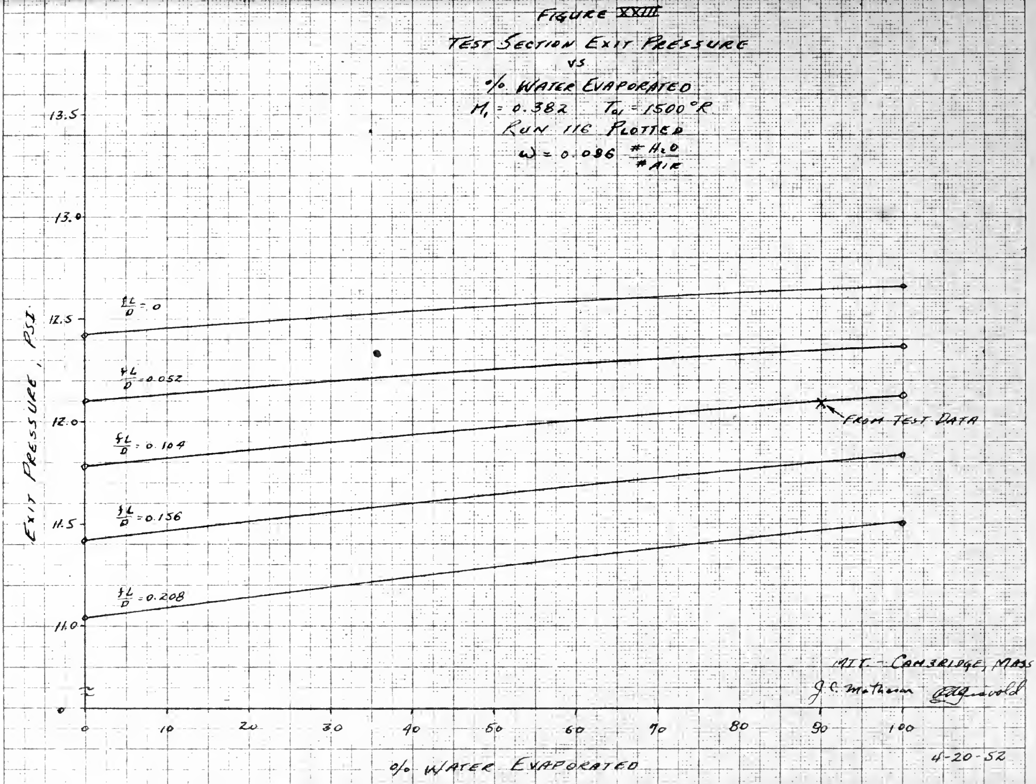


FIGURE XXIII
TEST SECTION EXIT PRESSURE
VS
% WATER EVAPORATED
$M_1 = 0.382$ $T_{01} = 1500°R$
RUN 116 PLOTTED
$\omega = 0.086 \frac{\# H_2O}{\# AIR}$
13.5
13.0
12.5
12.0
11.5
11.0
EXIT PRESSURE, PSI
$\frac{fL}{D} = 0$
$\frac{fL}{D} = 0.052$
$\frac{fL}{D} = 0.104$
$\frac{fL}{D} = 0.156$
$\frac{fL}{D} = 0.208$
FROM TEST DATA
0
0 10 20 30 40 50 60 70 80 90 100
% WATER EVAPORATED
MIT - CAMBRIDGE, MASS
J. C. Matheson
4-20-52

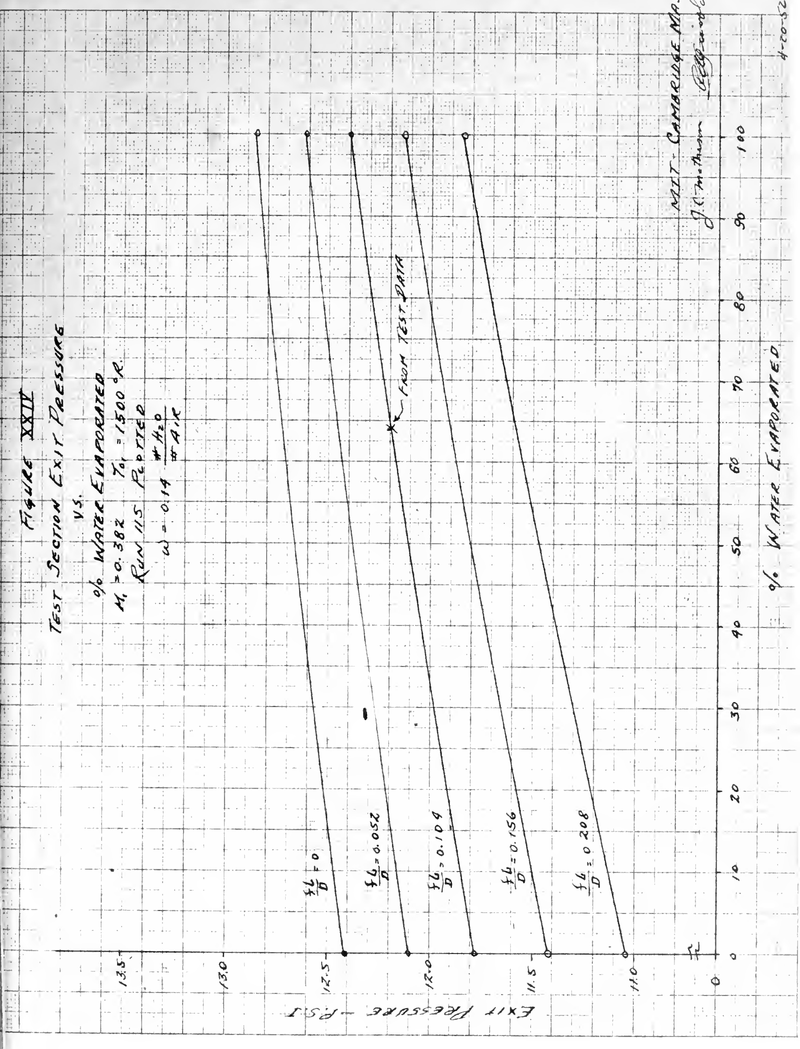
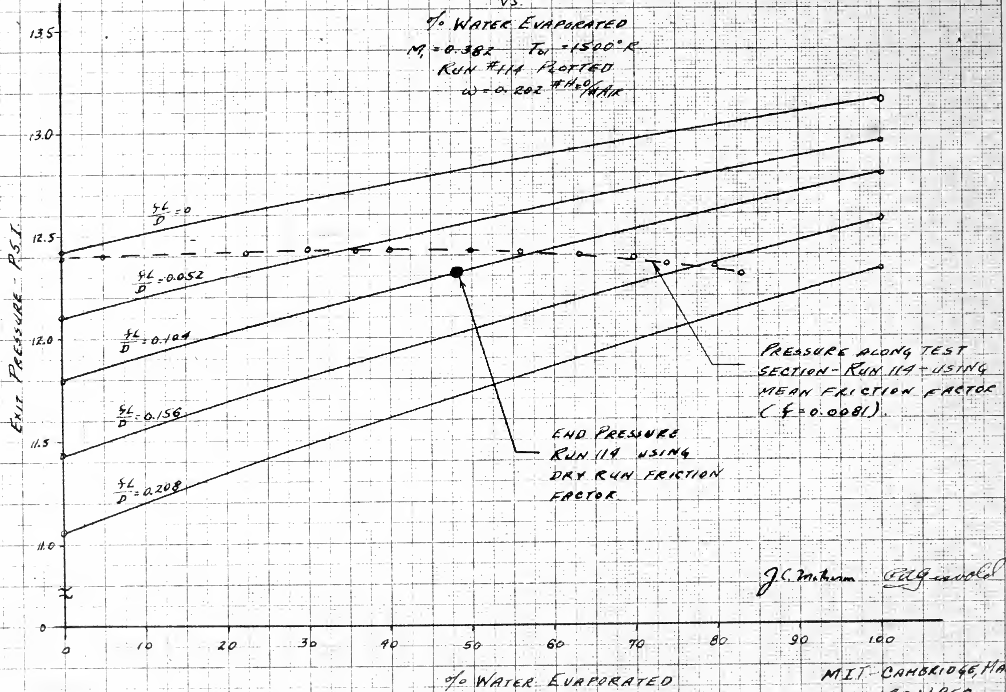


FIGURE XXII
TEST SECTION EXIT PRESSURE
VS.
% WATER EVAPORATED
$M_1 = 0.382$ $T_{01} = 1500\,°R.$
RUN 115 PLOTTED
$\omega = 0.14 \frac{\# H_2O}{\# AIR}$
FROM TEST DATA
$\frac{fL}{D} = 0$
$\frac{fL}{D} = 0.052$
$\frac{fL}{D} = 0.104$
$\frac{fL}{D} = 0.156$
$\frac{fL}{D} = 0.208$
EXIT PRESSURE - PSI
11.0
11.5
12.0
12.5
13.0
13.5
0
10
20
30
40
50
60
70
80
90
100
% WATER EVAPORATED
MIT - CAMBRIDGE MASS
4-20-52

FIGURE XXV

TEST SECTION EXIT PRESSURE
VS.
% WATER EVAPORATED

$M_1 = 0.382$ $T_{01} = 1500°R$
RUN #114 PLOTTED
$\omega = 0.202$ #H_2O/#AIR



J.C. Mitchum [signature]

MIT - CAMBRIDGE, MASS.
1 MAY 1952

exit pressure measured in run #114. The percent evaporation obtained (80%) was used to obtain a refined mean friction factor. This is illustrated in Figure XXVIII. It is noted that the assumption of friction factor variation with length is to some extent arbitrary. The corrected mean friction factor indicated 83% evaporation. With this point and measured pressure readings along the test section (plotted in Figure XXV) it was possible to obtain in Figure XXVI the variation of percent evaporation with length for the injection rate of run #114. The decreasing rate of evaporation with length is believed due to the appreciably greater temperature differences between hot gas and injected water in the upstream portion of the test section. It is realized that the preceding analysis is not rigorous. It is considered reasonable, and offers qualitative information as to the history of the evaporation process within the test section.

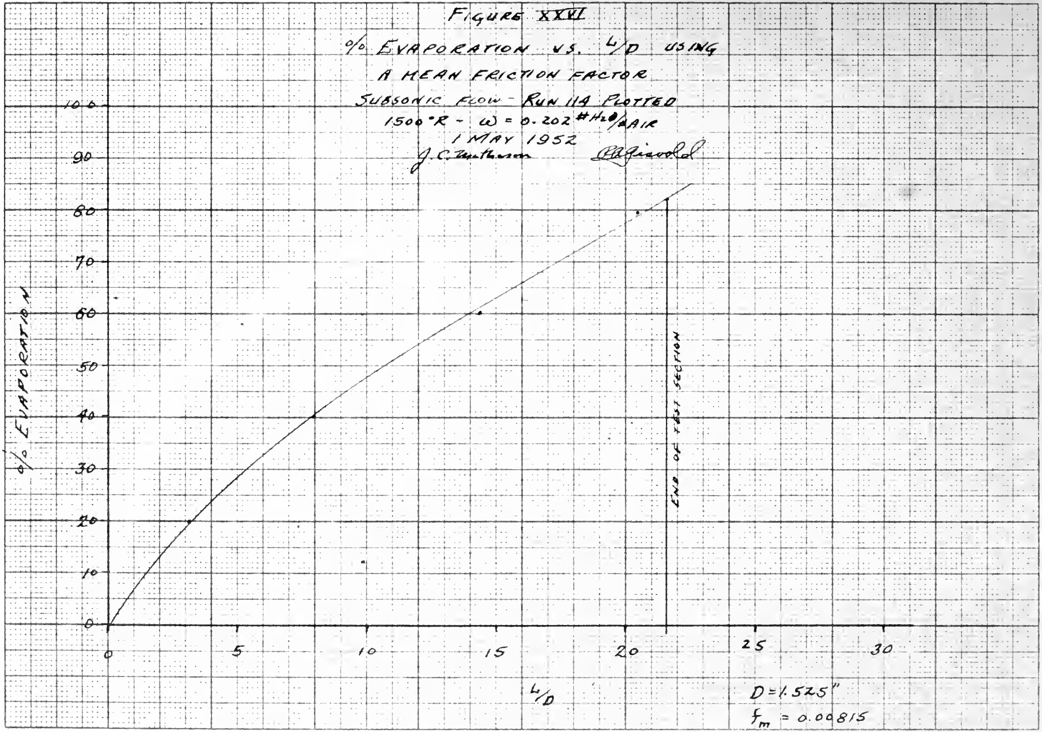
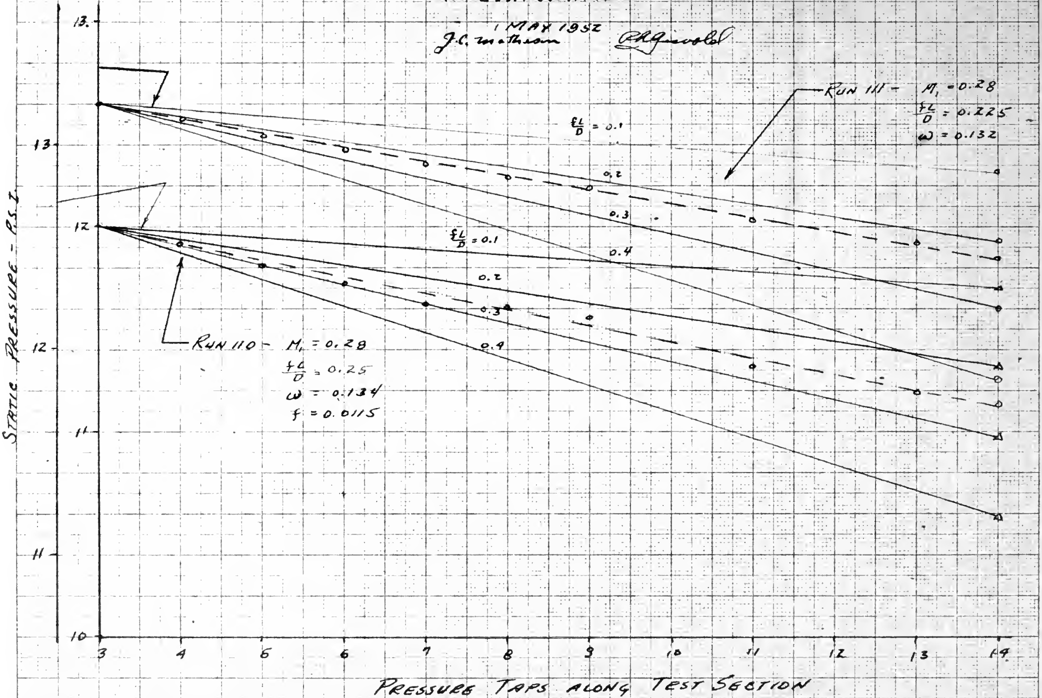


FIGURE XXVI

% EVAPORATION VS. L/D USING
A MEAN FRICTION FACTOR
SUBSONIC FLOW - RUN 11A PLOTTED
1500°R - ω = 0.202 #H_2O/#AIR
1 MAY 1952
J. C. Mathison   [signature]

FIGURE XXVII
ESTIMATE OF FRICTION FACTOR
ROOM TEMPERATURE WITH
NO EVAPORATION

1 MAY 1952
J.C. Matheson



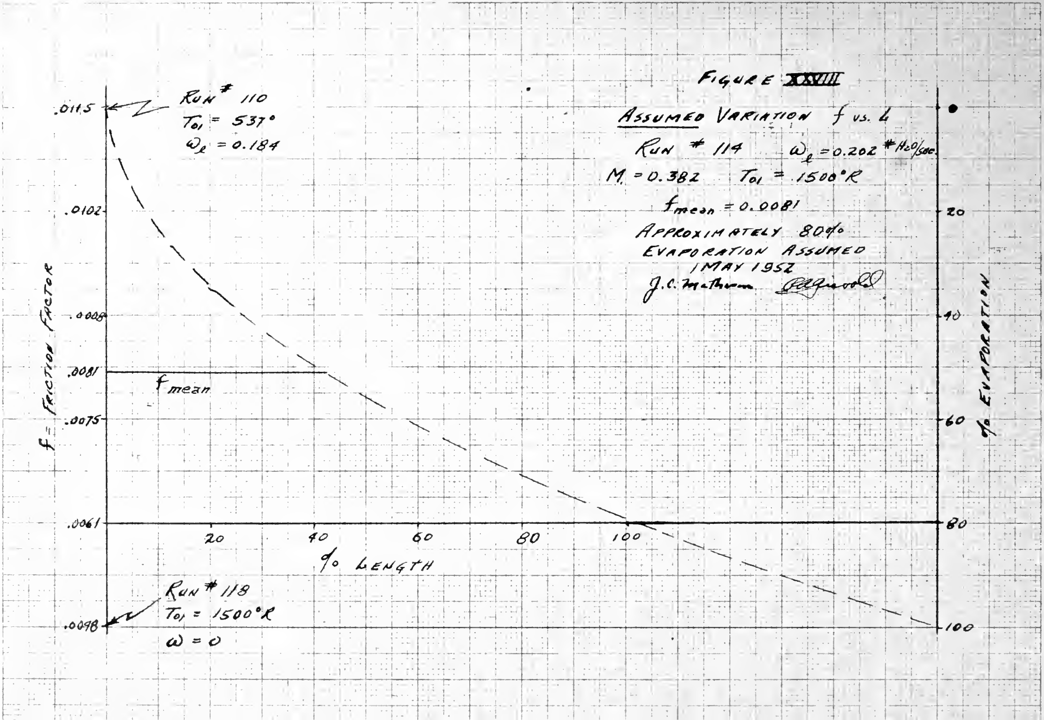


FIGURE XXVIII
ASSUMED VARIATION f vs. L
RUN # 114 ω_l = 0.202 # H2O/SEC
M1 = 0.382 T01 = 1500°R
f_mean = 0.0081
APPROXIMATELY 80%
EVAPORATION ASSUMED
1 MAY 1952
J.C. Mathews
RUN # 110
T01 = 537°
ω_l = 0.184
RUN # 118
T01 = 1500°R
ω = 0
f_mean
.0115
.0102
.0088
.0081
.0075
.0061
.0048
20
40
60
80
100
% LENGTH
f = FRICTION FACTOR
% EVAPORATION

V. CONCLUSIONS

The following conclusions drawn from the investigation, apply specifically to aerothermopressor operation at atmospheric inlet pressure with an initial Mach number of approximately 2.0 for supersonic flow, and approximately 0.4 for subsonic flow. In a qualitative sense they are believed applicable to the successful design of any aerothermopressor.

1. In supersonic and subsonic operation, effectiveness increases with rate of injection to a maximum at or near the point of stream saturation.
2. With axial water injection, the position of injection has a marked influence on the test section entrance Mach number. For the supersonic case, the Mach number decreases as the injection point is moved from nozzle entrance to exit. In the subsonic case it increases.
3. In supersonic operation effectiveness increases with increase in inlet temperature.
4. The increase in exit stagnation pressure due to water injection is greater for supersonic operation than for subsonic operation.
5. For a given rate of injection and incomplete evaporation, more water is evaporated in subsonic operation than in supersonic.
6. For a given mass rate of air flow, the amount of water that may be evaporated is greater in the subsonic case than in the supersonic case.
7. A greater percentage of the water injected is evaporated at lower rates of injection.

8. Wall friction in small scale tests has a marked influence on aerothermopressor effectiveness. The effective friction factor may exceed 150% of the dry run value. The average friction factor along the test section increases with increased water injection rate.
9. A test section length of approximately four feet for this test setup is necessary to obtain complete evaporation with saturated exit conditions for both subsonic and supersonic flow.
10. An increased test section diameter and an effective diffuser is essential for successful operation under either subsonic or supersonic conditions.
11. The method of theoretical analysis employed is considered to adequately predict exit conditions. Its success is dependent upon reliable estimates of friction factor. It is not as effective in providing information on the variation of effects with length along the test section as for predicting end conditions.

VI. RECOMMENDATIONS

1. It is suggested that further analysis be made of data obtained at 1100°R. and 1300°R. inlet temperatures, and at 1500°R. with injection at nozzle throat and entrance.
2. In order to obtain further supersonic data with the present nozzle, it is recommended that the test section be shortened approximately six inches to eliminate choking effects, the lower stagnation chamber increased in size, and a diffusor be fitted to the test section exit. The latter would provide more reliable stagnation pressures and a better measure of the net effectiveness as an aerothermopressor.
3. To obtain better subsonic data, it is recommended that a converging nozzle be employed, designed to deliver a higher subsonic Mach number than the present nozzle. The present design, intended primarily for supersonic operation, resulted in unstable behavior and an inherent low Mach number when operated under subsonic conditions.
4. In further subsonic tests, it is recommended that the water injection system be modified to permit greater injection rates. This would entail use of higher air pressure or a redesign of injection needles to permit greater flow rates at present pressure.
5. Test data indicates the present design conservative. It is believed that the Gas Turbine Laboratory air ejector and gas furnace capacity will support a greater mass rate of flow. A test section diameter of about 3 inches is

considered feasible. The resultant reduction in wall friction should considerably improve performance in both supersonic and subsonic operation.

APPENDIX A

DETERMINATION OF TEST EQUIPMENT CHARACTERISTICS

A. Basis of Design of Components:

With the temperature limited to the 1100° to 1500°R. range and the furnace limited from previous tests to about 0.2 lbs. of air per second, combinations of Mach number, area ratios and lengths for these limitations were tabulated in Table I. The table was analyzed to select the best combination of length and Mach number which would give a reasonably high Mach number under subsonic operation.

TABLE I

TABULATION OF NOZZLE-TEST SECTION CHARACTERISTICS FOR MACH NUMBERS AND FLOW RATES

	Pounds Air Per Second					
	0.2		0.4		0.6	
Temp. (T_{01}) °R.	1000	1500	1000	1500	1000	1500
Nozzle Area	0.827	1.01	1.65	2.02	2.475	3.03
Nozzle Diameter	1.024	1.127	1.440	1.60	1.772	1.96
Test Section:						
Mach No. 1.5						
(A/A*=1.1762)						
Area	0.972	1.187	1.944	2.375	2.91	3.56
Diameter	1.112	1.228	1.57	1.735	1.923	2.125
Length	12.6	13.91"	17.8"	19.65"	21.8"	24.1"
(4fL/D=0.13605)						
Mach No. 1.75						
(A/A*=1.3865)						
Area	1.144	1.40	2.285	2.797	3.425	4.20
Diameter	1.204	1.332	1.702	1.883	2.085	2.31
Length	22.58"	24.[illegible]8"	31.9"	35.25"	39.1"	43.3"
(4fL/D=0.22504)						
Mach No. 2.00						
(A/A*=6875)						
Area	1.394	1.704	2.78	3.41	4.17	5.11
Diameter	1.33	1.47	1.88	2.08	2.3	2.[illegible]45
Length	33.8"	37.3"	47.75"	52.8"	58.4"	64.7"
(4fL/D=0.30499)						

Assumed f=0.003

The following characteristics were set from analysis of Table I:

Air Flow Rate	-	0.214 lbs. air per second
Diameter of Test Section	-	1.525"
Supersonic Mach number	-	2.0
Subsonic Mach number	-	0.35
Area of Nozzle	-	1.0824 Sq. In.
Length of Test Section	-	36"

Figure XXXII shows details of the test section-nozzle design.

B. Nozzle Design:

The design of the nozzle to produce a Mach number of 2.0 at the exit was based on Foelsch(6) design criteria for supersonic nozzles. The exit diameter was fixed by the straight smooth heat conduction tube which was readily available. For this project, a length of 1.525" I.D. copper-nickel tubing was used. The Foelsch design was modified to incorporate a $7\frac{1}{2}^{o}$ included angle in the diffuser section of the nozzle to permit its more efficient use in subsonic tests. Straight sections were included at the throat and exit of the nozzle for inclusion of pressure taps. The nozzle design details are shown in Figure XXXII.

C. Test Section Design:

The test section was an available straight section of 1.525" I.D. copper-nickel tubing with pressure taps every 3" along its length. Figure XXXII shows the details of assembly of the test section and nozzle. A diffuser was not included at the exit of the test section as the predicted pressure drop through the test section was well within the available drop of 14 psia.

D. Water Injection Equipment:

Two desirable features to be incorporated into the water

injection system were axial injection and high initial velocity. Axial injection was possible by running the injection tube through the top of the upper stagnation chamber. The assumed rate of injection was 0.1 lbs. of water per lb. of air for T_{01}=1500°R. and with M=2.0. This was desired based on the analysis of the amount of water necessary for stream saturation under these initial conditions.

With this flow of water and a predicted air flow at M=2.0 of 0.214 lbs. air per second it was necessary to inject 0.02 lbs. water per second or 72 lbs. water per hour. With a pressure of 1100 psia. on the water, it would be possible to attain 400'/sec. injection velocity. This is far from the 4000'/sec. required for no drag at M=2.0.

If 400'/sec. injection velocity and 0.02 lbs. water/second flow were used,

$$\text{Area of Injection} = \frac{\text{Mass Rate Flow}}{V} = \frac{0.02 \times 144}{64.4 \times 400} \quad (1)$$

$$= 0.000112 \text{ Sq. In.}$$

$$\text{Four Holes} = \text{Area} = 4\pi d^2/4 = 0.000112$$

$$\text{Hole Diameter} = 0.00596''$$

This diameter is considered too small to preclude fouling.

Using the same procedure for city water pressure, the following results were obtained:

$$\text{Velocity} = \sqrt{\Delta p \frac{2g}{\rho}} = \sqrt{64} \times 12 = 100'/\text{sec.} \quad (2)$$

$$\text{Area} = 0.000448$$

$$\text{Diameter using four holes} = 0.01066''$$

In view of the above preliminary calculations, it was decided to use six injection hypodermic needles 0.025" I.D.

These were sufficiently large to resist fouling and in a readily available size. Attempting to obtain high velocity injection was considered unfeasible because of the high pressure requirements. The needles were mounted in the injection tube as shown in Figure XXXIII and the injection tube mounted as shown in Figure XXXI. The needles were made 6" long to permit their reaching into the test section without serious interference with flow at the throat. The six needle pattern gives good flow distribution.

The water reservoir tank was used for water injection. The tank was filled from the city water pressure manifold and after filling was connected to the water injection tube through the flowmeter. Air pressure was placed on the water tank through the pressure regulating valve. This valve was controlled manually for the water flow rate desired in the flowmeter. A constant air pressure was maintained on the water in the tank by the air pressure regulating valve. This resulted in constant water flow to the injection tubes.

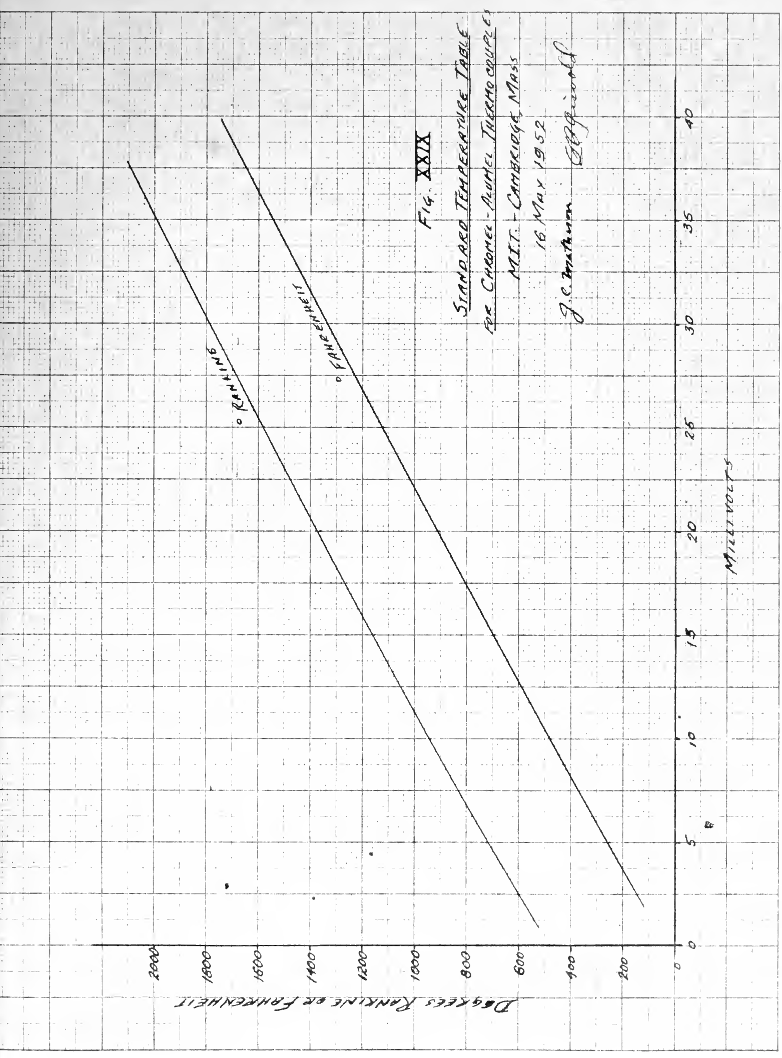


FIG. XXIX
STANDARD TEMPERATURE TABLE
FOR CHROMEL-ALUMEL THERMOCOUPLES
M.I.T. - CAMBRIDGE, MASS
16 MAY 1952

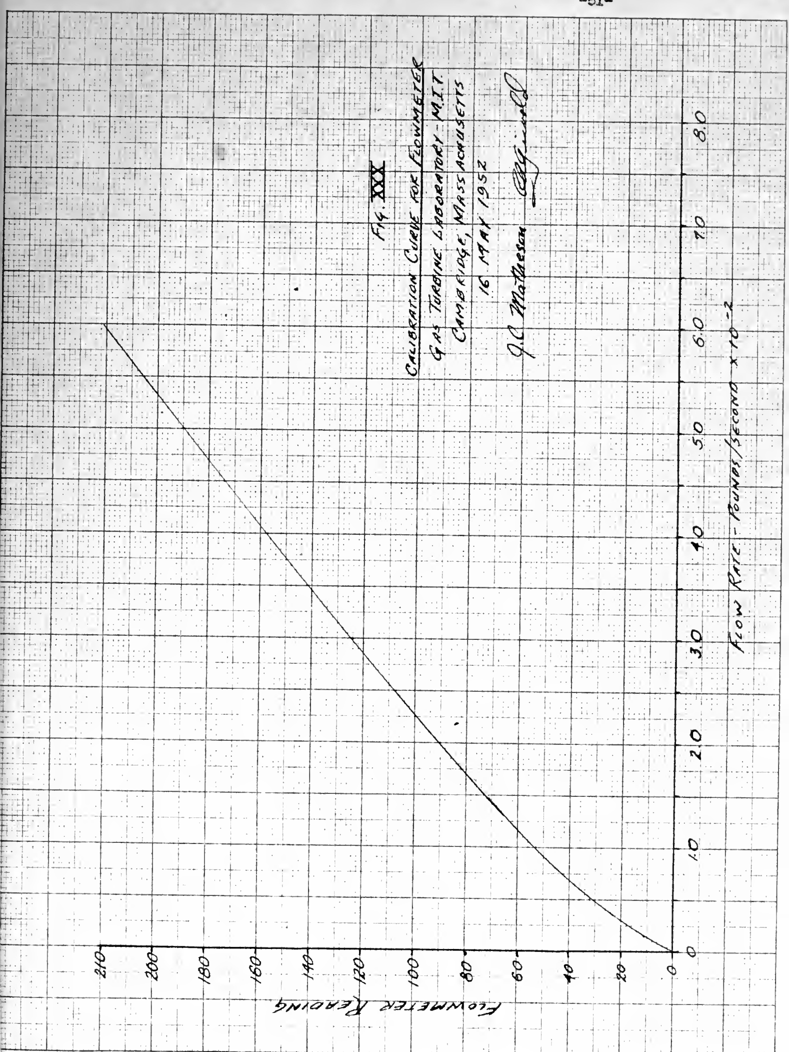
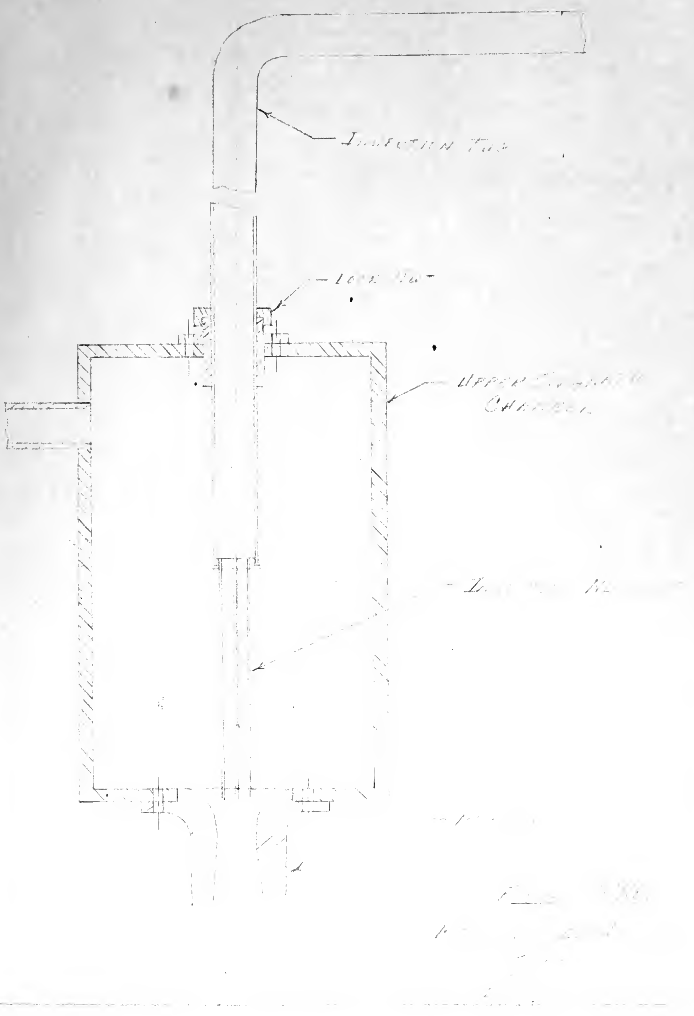
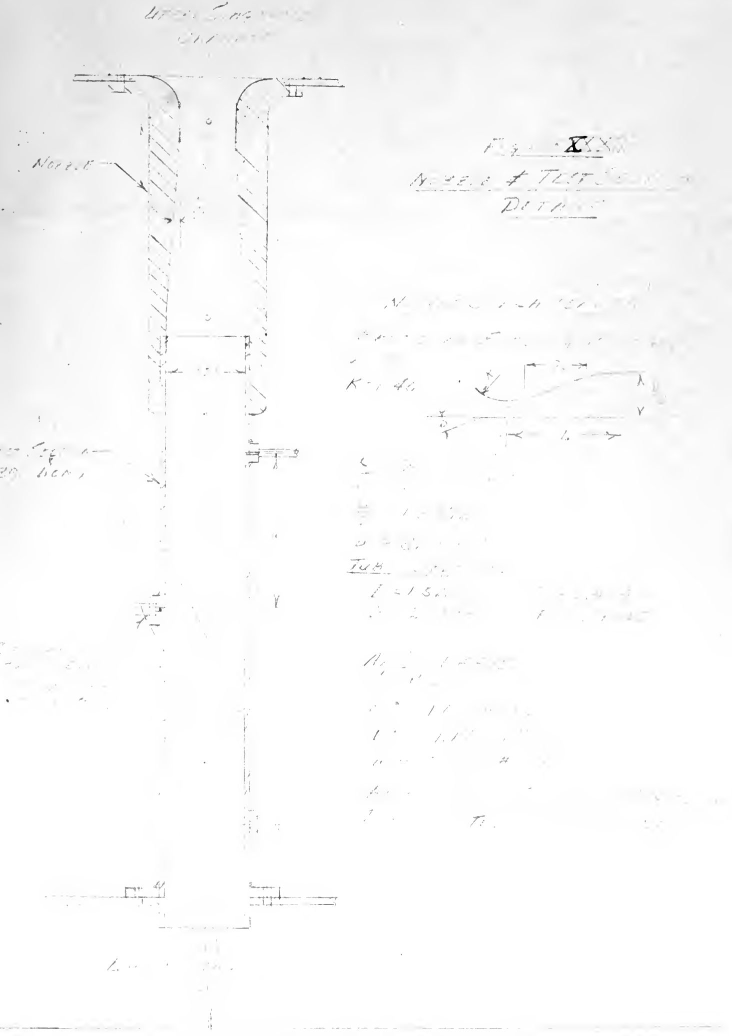
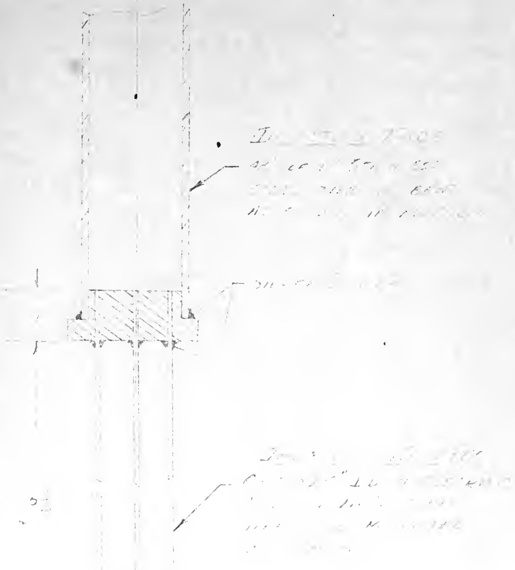


FIG. XXX
CALIBRATION CURVE FOR FLOWMETER
GAS TURBINE LABORATORY - M.I.T.
CAMBRIDGE, MASSACHUSETTS
16 MAY 1952
J.C. Matheson
FLOWMETER READING
0
20
40
60
80
100
120
140
160
180
200
210
FLOW RATE - POUNDS/SECOND x 10^-2
0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0







APPENDIX B

ORIGINAL DATA

TABLE II
TABULATION OF DATA FOR SMALL SCALE AEROTHERMOPRESSOR
CONSTANT AREA TESTS
MIT - CAMBRIDGE, MASS. - 16 MAY 1952

RUN NUMBER	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29
INLET TEMPERATURE, °R.	1136	1144	1179	1162	1165	1164	1520	1515	1490	1510	1510	1510	1520	1320	1370	1300	1295	1280	1280	1110	1100	1090	1070	1330	1520
OUTLET TEMPERATURE, °R	827	670	885	555	575	575	1312	1287	560	700	860		560	560	560	560	580	750	700	550	550	550	900	1100	1250
ROOM TEMPERATURE, °F	78	78	78	78	78	78	76	76	80	80	80	80	80	80	80	80	80	80	80	80	80	80	80	80	80
										SUPERSONIC															
PRESSURES - CM. HG. ABS.																									
UPPER STAG. ~~CHAMBER~~	75.45	75.3	75.4	75.4	75.4	75.4	75.27	75.27	75.47	75.37	75.37		75.47	75.37	75.37	75.37	75.37		75.37	75.37	75.37	75.37	75.27	75.27	75.37
#2 TAP (THROAT)	35.87	40.02	40.22	40.52	41.32	41.82	36.47	36.27	40.77	40.07	39.67		41.37	41.07	40.87	40.27	39.97		39.67	41.27	40.77	40.21	35.47	35.77	36.37
#3	10.87	10.92	10.92	11.12	11.62	11.92	10.97	10.87	11.37	11.27	11.17		11.87	11.67	11.47	11.07	11.07		10.87	11.57	11.27	11.07	10.87	10.77	10.87
#4	10.27	10.72	10.82	11.52	12.02	12.42	10.47	10.37	11.47	11.27	10.97		11.77	11.67	11.57	11.07	11.07		10.87	12.07	11.67	11.37	10.07	9.97	10.17
#5	12.07	12.02	12.12	12.52	12.92	13.02	11.57	11.47	12.07	11.47	11.37		12.17	12.37	12.37	11.87	11.67		11.57	12.87	12.87	12.27	11.47	11.27	11.17
#6	12.17	12.42	12.12	12.02	12.42	12.62	12.17	11.87	11.47	11.47	11.57		11.47	11.87	11.77	11.57	11.67		11.87	12.37	12.17	12.07	11.37	11.37	11.47
#7	12.97	13.22	13.02	12.92	13.32	13.42	12.87	12.67	12.17	12.07	12.17		12.07	12.57	12.47	12.27	12.47		12.47	13.27	13.27	12.97	12.57	12.37	12.37
#8	22-17*	14.62	13.12	12.82	13.12	13.42	11-16*	13.37*	11.97	12.07	12.17	UNSTABLE - PROBABLE STEAM FORMATION IN NEEDLES.	11.77	12.17	12.17	12.27	12.47	UNSTABLE - PROBABLY STEAM FORMATION IN NEEDLES	12.57	13.37	13.07	13.07	13.07	13.07	13.17
#9	27	15.02	14.42	14.02	13.92	14.02	24-27	23	12.97	13.17	13.47		12.67	13.27	13.37	13.37	13.67		13.87	14.07	14.07	14.27	16.87*	26*	15.77
#10	29	15.32	14.22	13.72	13.52	13.62	27.67	26.5	12.57	13.07	13.37		12.27	12.87	12.97	13.07	13.37		13.57	13.77	13.57	13.97	24	24	24.77
#11	29.3	16.22	15.02	14.22	16.02	14.22	28.67	28.67	12.47	13.37	14.07		12.17	13.07	13.27	13.47	13.97		14.47	14.47	14.47	14.97	27	26	26.77
#12	29.57	16.70*	15.42	14.62	14.22	14.32	29.17	29.17	12.57	13.37	14.27		12.27	13.07	13.17	13.37	14.27		14.97	14.57	14.57	15.17	28	27	28
#13	29.20	22.72	16.52	15.32	14.82	15.02	29.87	28.57	13.27	14.07	15.07		12.87	13.67	13.87	13.97	14.97		14.97	15.37	15.57	16.07	28.3	28	28
#14	27.67	23.72	27.12	15.52	15.02	15.22	27.57	27.37	13.37	14.37	15.47		12.87	13.87	13.97	14.17	15.17		16.37	15.57	15.67	16.27	27	27	27
LOWER STAG. CHAMBER	16.87	17.22	17.42	17.52	17.62	17.52	16.37	16.07	16.87	16.57	16.47		16.97	16.87	16.87	16.77	16.77		16.77	17.77	17.67	17.47	16.87	16.27	15.97
EJECTOR TANK	19.12	19.42	19.42	19.82	19.82	19.72	18.37	18.37	19.07	18.97	18.77		19.37	19.27	19.27	19.07	19.07		18.97	20.07	20.00	19.87	19.17	18.57	18.37
WATER INJECTION POSITION	ENT.	ENT.	ENT.	ENT.	ENT.	ENT.	ENT.	ENT.	ENT.	ENT.	ENT.		ENT.	ENT.	ENT.	ENT.	ENT.	ENT.	ENT.	ENT.	ENT.	ENT.	ENT.	ENT.	ENT.
FLOWMETER READING	NONE	41.0	72.0	105	153	178	NONE	NONE	138	103	85.5	~75	176	158	141.5	117	93	~60	69	158	124	89	NONE	NONE	NONE
POUNDS WATER/SEC.	[illegible]	0.0087	0.0245	0.0245	0.0385	0.0465			0.0342	0.024	0.0188		0.0457	0.040	0.0352	0.028	0.021		0.0145	0.040	0.030	0.0198			
SPRAY	No	Yes	Yes	Yes	Yes	Yes	Yes	No	No	No	No	-	No	No	No	No	No		No	No	No	No	No	No	No
IMPACT TUBE, CM. HG. ABS.	35.87	38.22	40.72	31.82	32.82	NONE	NONE	NONE	No	No	No		No	No	No	No	No		No	No	No	No	No	No	No
EJECTOR VALVE SETTING	FULL OPEN	F.O.	F.O.	F.O.	F.O.	F.O.	F.O.	F.O.	F.O.	F.O.	F.O.		F.O.	F.O.	F.O.	F.O.	F.O.		F.O.	F.O.	F.O.	F.O.	F.O.	F.O.	F.O.
AIR FLOW - #/SEC.	.252	.252	.252	.252	.252	.252	.214	.214	0.216	0.216	0.216		0.216	.231	.231	.231	.231		.231	.252	.252	.252	.252	.231	.214
ω = #H2O/#AIR	0	.0347	.0575	.0973	.153	.185	0	0	0.1585	0.1111	0.0872		0.2115	.173	.152	.121	.091		.0628	.159	.119	.0786	0	0	0
P_{14}/P	.3675	.315	.2275	.206	.199	.202	.366	.364	.177	.1905	.2053		.1705	.184	.1855	.188	.201		.217	.2065	.208	.216	.3585	.3585	.358

TABLE III

TABULATION OF DATA FOR SMALL SCALE AEROTHERMOPRESSOR

CONSTANT AREA TESTS

M.I.T. - CAMBRIDGE, MASS.

RUN NUMBER	30	31	32	33	34	35	36	37	38	39	40
INLET TEMP. °R.	1500	1500	1500	1500	1500	1300	1300	1300	1300	1300	1300
OUTLET TEMP. °R.	560	560	750	940	920	550	550	550	630	800	
ROOM TEMP. °F	80	80	80	81	81	82	82	82	82	82	
	←									SUPERSONIC	
PRESSURES - CM. Hg. ABS.											
UPPER STAG. CHAMBER	75.4	75.3	75.3	75.3	75.4	75.4	75.4	75.4	75.4	75.3	75.3
#2 TAP (THROAT)	46.4	46.3	46.0	45.3	44.6	46.2	46.2	46.0	45.2	44.6	43.8
3	12.3	11.9	11.4	11.2	11.2	11.9	11.8	11.5	11.2	11.1	11.1
4	12.6	12.0	11.4	11.1	11.0	12.4	12.0	11.8	11.3	11.0	10.8
5	13.0	12.6	12.0	11.9	11.8	13.0	12.8	12.6	12.2	12.0	12.0
6	12.2	11.8	11.7	12.0	12.1	12.3	12.1	11.9	12.0	12.0	12.3
7	12.7	12.4	12.3	12.5	12.6	13.0	12.8	12.8	12.8	12.9	12.9
8	12.3	12.0	12.3	12.6	12.8	12.7	12.4	12.4	12.8	13.0	↓
9	13.3	13.1	13.5	13.9	14.3	13.6	13.6	13.7	14.0	14.4	
10	12.9	12.7	13.3	13.7	14.5	13.3	13.3	13.4	13.8	14.3	
11	12.9	12.7	13.8	14.5	↓	13.5	13.5	13.7	14.6	15.3	
12	12.9	12.7	13.9	15.2		13.8	13.6	14.0	15.1	15.8	UNSTABLE
13	13.4	13.4	14.5	16.0	UNSTABLE	14.3	14.2	14.4	16.0	16.8*	
14	13.6	13.5	14.8	16.5		14.4	14.3	14.6	16.5	20.8	
LOWER STAG. CHAMBER	17.2	16.8	16.6	16.7		17.9	17.5	17.5	17.3	17.6	
EJECTOR TANK	19.4	19.0	18.8	18.7		20.1	19.8	19.8	19.6	19.2	
IMPACT TUBE	50.9	49.8	48.8	48.3		51.0	49.3	48.8	46.8	44.8	
WATER INJECTION:											
POSITION	THROAT	THROAT	THROAT	THROAT	THROAT	THROAT	THROAT	THROAT	THROAT	THROAT	THROAT
FLOWMETER READING	172	146	101	77	55	155	133	114	70	62	44
#/SEC.	.0445	.0364	.0232	.0165	.0105	.0392	.0327	.0272	.0145	.0125	
SPRAY	No	No	No	No	No	No.	No	No	No.	No.	
EJECTOR VALVE SETTING	F.O.	F.O.	F.O.	F.O.	F.O.	F.O.	P.O.	P.O.	P.O.	P.O.	
AIR FLOW - #/SEC.	.214	.214	.214	.214	.214	.231	.231	.231	.231	.231	
ω = # H_2O/# AIR.	.208	.170	.1085	.077	.0491	.170	.1417	.118	.0827	.0541	
P_{14}/P_0	.1805	.1795	.1965	.219		.191	.190	.1935	.219	.276	

RUN NUMBER	41	42	43	44	45	46	47	48	49	50
INLET TEMP. °R.	1100	1100	1070	1060	1050	1050	1050	1500	1500	1500
OUTLET TEMP. °R.	550	550	540	540	600	700	720	1270	555	580
ROOM TEMP. °F	81	81	81	81	81	81	81	75	75	75
										→
PRESSURES - CM. Hg. ABS.										
UPPER STAG. CHAMBER	75.3	75.3	75.3	75.3	75.3	75.3	75.3	75.4	75.4	75.5
#2 TAP (THROAT)	46.3	46.3	46.2	45.5	44.3	43.9	44.2	39.4	39.2	39.3
3	12.7	12.2	11.8	11.4	11.2	11.1	11.1	11.9	12.7	13.0
4	13.6	13.0	12.3	11.8	11.3	11.0	11.1	11.6	14.9	14.3
5	14.0	13.4	13.4	12.8	12.2	12.2	12.2	12.1	15.2	14.8
6	13.9	13.1	12.6	12.2	12.1	12.3	12.2	12.8	14.9	14.4
7	14.3	13.8	13.7	13.3	13.2	13.3	13.2	13.5	14.9	14.6
8	14.6	14.2	13.7	13.1	13.3	13.5	13.5	14.2	14.6	14.6
9	15.3	14.8	14.3	14.4	14.8	15.0	14.9	21.9*	13.8	15.0
10	15.4	14.7	14.2	14.2	15.0	15.4	15.3	26.9	14.3	14.4
11	15.5	15.1	15.0	15.2	15.9	16.3	15.3	28.9	14.4	14.9
12	15.6	15.4	15.1	15.3	16.5	16.8*	↓	29.4	14.5	15.0
13	16.4	16.1	16.0	16.3	18.8*	22.8	UNSTABLE	28.9	15.0	15.4
14	16.8	16.3	16.2	16.7	22.3	23.8		27.8	15.1	15.5
LOWER STAG. CHAMBER	18.8	17.9	17.8	17.7	17.8	17.8		11.3	12.9	16.9
EJECTOR TANK	21.1	20.1	20.0	19.8	19.8	19.8		13.5	15.2	19.1
IMPACT TUBE	51.8	52.3	49.8	46.3	42.8	41.8		34.4	43.3	48.3
WATER INJECTION:										
POSITION	THROAT	THROAT	THROAT	THROAT	THROAT	THROAT	THROAT	EXIT	EXIT	EXIT
FLOWMETER READING	193	151	123	88	53	45	NONE	NONE	180	143
#/SEC.	.0515	.038	.0297	.019	.010	.0092	?		.047	.0355
SPRAY	No.	No	No	No	No	No	No	No	No	No
EJECTOR VALVE SETTING	F.O.	F.O.	F.O.	F.O.	F.O.	F.O.	F.O.	F.O.	F.O.	F.O.
AIR FLOW - #/SEC.	.252	.252	.252	.252	.252	.252		.2135	.2135	.2135
ω = # H_2O/# AIR.	.214	.151	.118	.0755	.0397	.0365	0	0	.220	.166
P_{14}/P_0	.223	.216	.215	.222	.296	.316		.368	.200	.205

RUNS	30-47	48-50
DATE	3/27/52	4/2/52
BAROM. PRESS. - MM. Hg	762.6	764.4

TABLE IV

TABULATION OF DATA FOR SMALL SCALE AEROTHERMOPRESSOR
CONSTANT AREA TESTS

P.B. Griswold
MIT - CAMBRIDGE, MASS.

RUN NUMBER	51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71
INLET TEMP. °R.	1500	1490	1300	1300	1300	1300	1300	1100	1100	1100	1100	1100	1100	1310	1300	1120	1120	1100	1500	1500	1480
OUTLET TEMP. °R.	740	850	550	560	560	670	650	550	540	540	540	620	920	1090	1150	600	700	850	1300	610	860
ROOM TEMP. °F.	75	75	75	75	75	75	75	75	75	75	75	75	75	75	75	75	75	75	76	76	78
	←					SUPERSONIC								→	←		SUBSONIC				→
PRESSURES - CM. Hg. ABS.																					
UPPER STAG. CHAMBER	75.5	75.5	75.5	75.4	75.4	75.4	75.4	75.4	75.4	75.4	75.4	75.4	75.4	75.4	75.3	75.7	75.7	75.6	75.5	76.1	76.1
#2 TAP (THROAT)	39.4	39.4	38.6	38.0	38.4	38.5	38.6	37.4	37.4	37.4	37.4	37.4	37.4	38.9	38.7	38.5	38.6	38.5	43.9	42.9	42.9
#3	13.4	13.6	12.5	12.4	12.7	12.9	13.1	12.2	12.4	12.4	12.4	12.5	11.7	11.7	46.1	48.4*	45.6*	46.3*	65.4	64.8	65.1
4	13.9	13.5	14.8	14.7	14.2	13.6	13.3	14.9	14.4	13.9	13.5	12.9	11.0	11.1	49.6	51.1	49.6	49.5	65.4	65.5	65.5
5	14.5	14.2	15.4	15.4	14.7	14.3	13.9	15.7	15.1	14.7	14.4	13.9	12.0	12.0	49.7	52.4	50.6	50.5	65.2	65.7	65.5
6	14.2	14.1	15.2	15.2	14.5	14.1	13.9	15.9	15.1	14.7	14.2	13.9	12.5	12.6	49.4	52.8	51.0	50.5	64.9	65.7	65.6
7	14.7	14.8	15.3	15.4	14.8	14.9	14.7	16.2	15.6	15.2	15.0	14.9	13.1	13.4	49.0	52.9	51.1	50.5	64.4	65.7	65.5
8	14.9	15.1	15.1	15.2	14.9	15.1	15.1	16.1	15.6	15.5	15.4	15.4	13.9	14.1	48.7	53.0	51.1	50.5	64.2	65.7	65.5
9	15.4	15.8	15.2	15.4	15.2	15.7	15.9	16.6	16.1	16.0	16.1	16.2	17.9*	17.9*	48.3	53.1	51.1	50.6	64.0	65.7	65.5
10	15.1	15.9	14.8	14.9	14.6	15.6	16.2	16.6	16.1	16.0	16.1	16.6	25.9	25.9	47.6	52.9	50.9	50.4	63.6	65.5	65.3
11	15.8	16.5	15.1	15.2	15.3	16.2	16.7	16.6	16.1	16.1	16.4	17.0	27.4	27.9	47.3	52.7	50.6	49.8	63.2	65.4	65.1
12	16.1	16.9	15.3	15.3	15.3	16.4	17.3	16.7	16.3	16.2	16.7	17.5	28.4	28.4	46.8	52.5	49.4	49.5	63.0	65.3	65.0
13	15.9	17.9	15.8	15.9	15.8	17.2	18.3	17.6	17.1	17.1	17.5	18.7	28.4	28.4	46.4	52.5	49.4	49.3	62.7	65.2	64.9
14	17.1	19.9*	15.8	16.0	15.8	17.5	22.9*	18.0	17.2	17.2	17.9	22.9*	27.4	27.4	45.9	52.2	49.0	48.8	62.3	65.0	64.5
LOWER STAG. CHAMBER	18.1	17.7	18.6	17.4	17.4	17.4*	17.4	18.4	17.9	17.8	17.9*	17.4	17.1	16.9	45.0	51.8	49.6	48.2	61.8	64.9	64.3
EJECTOR TANK	19.9	19.9	20.6	19.7	19.7	19.4	19.4	20.7	20.3	20.1	19.9	19.8	19.4	19.0	46.1	53.1	50.6	49.3	62.9	65.6	65.1
IMPACT TUBE	48.9	46.9	49.9	50.3	47.9	47.9	44.9	49.9	49.4	47.9	46.9	44.9	39.4	40.4	55.9	58.4	56.9	56.5	69.4	69.6	69.4
WATER INJECTION:																					
POSITION	EXIT	EXIT	EXIT	EXIT	EXIT	EXIT	EXIT	EXIT	EXIT	EXIT	EXIT	EXIT	EXIT	EXIT	EXIT	EXIT	EXIT	EXIT	ENT.	ENT.	ENT.
FLOWMETER READING	115	97.5	180	179	138	100	75	175	149	125	100	75	NONE	NONE	NONE	160	120	80	NONE	159	117
FLOW - #/SEC.	.0272	.0225	.047	.047	.034	.023	.016	.045	.0375	.0304	.0232	.016				.041	.029	.0175		.040	.028
SPRAY	No.	No.	No.	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	YES	YES
EJECTOR VALVE SETTING	F.O.	F.O.	F.O.	F.O.	F.O.	F.O.	F.O.	F.O.	F.O.	F.O.	F.O.	F.O.	F.O.	F.O.	F.O.	P.O.	P.O.	P.O.	P.O	P.O.	P.O.
AIR FLOW - #/SEC.	.2135	.2135	.231	.231	.231	.231	.231	.252	.252	.252	.252	.252	.252	.231	.237	.250	.250	.250	.250	0.216	0.216
ω = #H_2O/# AIR	.1275	.1055	.214	.214	.147	.0995	.0693	.179	.149	.1208	.0921	.0635	0	0	0	.164	.116	.070	0	0.185	0.1295
P_{14}/P_1	.2262	.2638	.2093	.212	.2093	.232	.304	.2382	.228	.228	.238	.304	.363	.363	.610	.689	.661	.645	.824	.855	.849

RUNS	51 - 68	69 - 71
DATE	4/2/52	4/4/52
BAROMETRIC PRESS.	764.4 Mm. Hg.	762.2

* DENOTES SHOCK

TABLE V

TABULATION OF DATA FOR SMALL SCALE CONSTANT AREA AEROTHERMOPRESSOR TESTS

MIT - CAMBRIDGE, MASS.

RUN NUMBER	72	73	74	75	76	77	78	79	80	81	82	83	84	85	86	87	88	89	90	91	92
INLET TEMP. °R.	1500	1500	1500	1300	1300	1300	1300	1300	1300	1100	1100	1100	1100	1100	1500	1500	1500	1500	1500	1300	1300
OUTLET TEMP. °R.	1040	780	1260	1070	1070	610	700	850	960	1010	580	600	740	630	940	870	780	690	580	750	590
ROOM TEMP. °F.	78	78	79	79	79	79	79	79	79	80	80	80	80	80	80	80	80	80	80	81	81
	←						SUBSONIC							→	←		SUPERSONIC				→
PRESSURES - CM. HG. ABS.																					
UPPER STAG. CHAMBER	76.1	76.1	76.1	75.8	75.8	75.9	75.8	75.8	75.8	75.7	75.6	75.7	75.7	75.7	75.3	75.3	75.3	75.3	75.3	75.3	75.3
#2 TAP (THROAT)	42.9	42.9	42.4	41.7	42.7	42.8	42.7	42.7	43.7	42.6	41.5	42.6	42.6	42.6	39.4	39.6	40.2	40.4	41.0	39.5	40.0
3	65.3	64.9	65.6	65.5	65.7	64.4	65.0	65.4	65.7	65.6	64.8	64.1	65.6	64.6	10.7	10.8	10.8	11.1	11.4	10.7	10.7
4	65.5	65.4	65.5	65.5	65.7	65.0	65.6	65.9	65.9	65.6	65.2	64.8	66.0	65.2	10.7	10.7	10.9	11.0	11.4	10.7	10.9
5	65.5	65.6	65.4	65.3	65.5	65.2	65.8	65.9	66.0	65.3	65.3	64.9	66.0	65.4	10.7	10.7	10.9	11.1	11.5	10.9	11.2
6	65.4	65.6	65.0	65.0	65.2	65.3	65.8	65.9	65.9	65.0	65.3	64.9	65.9	65.4	10.9	10.9	10.8	10.9	10.9	11.1	11.1
7	65.3	65.6	64.7	64.7	64.9	65.2	65.7	65.8	65.7	64.6	65.3	64.8	65.8	65.4	11.3	11.3	11.2	11.2	11.2	11.6	11.5
8	65.2	65.5	64.5	64.4	64.7	65.2	65.7	65.8	65.5	64.3	65.2	64.8	65.7	65.4	11.7	11.6	11.5	11.4	11.3	11.7	11.6
9	65.1	65.5	64.2	64.1	64.4	65.2	65.7	65.7	65.4	64.1	65.1	64.7	65.7	65.2	12.6	12.5	12.2	11.9	11.7	12.8	12.5
10	64.8	65.4	63.7	63.7	64.1	65.1	65.5	65.4	65.1	63.7	65.0	64.6	65.4	65.1	12.6	12.5	12.0	11.8	11.7	12.7	11.9
11	64.5	65.2	63.3	63.3	63.8	64.9	65.4	65.2	64.9	63.5	64.8	64.4	65.3	64.8	12.9	12.8	11.9	11.7	11.3	13.2	12.4
12	64.3	65.1	63.1	62.9	63.4	64.8	65.3	65.0	64.6	63.2	64.6	64.3	65.1	64.7	13.2	12.9	12.2	12.0	11.6	13.2	12.4
13	64.1	65.0	62.7	62.6	63.2	64.7	65.2	64.9	64.4	63.1	64.5	64.1	65.0	64.6	14.0	13.7	12.8	12.5	12.1	13.9	13.1
14	63.7	64.7	62.3	–	62.9	64.5	64.9	64.7	64.1	62.6	64.3	64.0	64.7	64.4	14.4	14.1	12.9	12.7	12.2	14.3	13.2
LOWER STAG. CHAMBER	62.8	64.5	61.8	62.2	62.2	64.3	64.7	64.4	63.7	62.1	64.1	63.7	64.3	64.6	22.1	24.6	23.2	23.8	24.3	23.0	24.2
EJECTOR TANK	64.0	65.4	63.0	63.0	63.0	65.0	65.4	65.2	64.2	63.0	64.9	64.6	65.1	64.0	24.2	24.5	25.1	25.7	26.1	24.9	26.1
IMPACT TUBE	69.4	69.6	69.4	–	69.8	69.3	69.8	69.8	69.8	69.7	69.3	68.6	70.0	69.2	46.2	45.7	45.7	45.2	44.7	46.2	45.7
WATER INJECTION:																					
POSITION	ENT.	ENT.	ENT.	ENT.	ENT.	ENT.	ENT.	ENT	ENT.	ENT	ENT	ENT	ENT	ENT	ENT	ENT.	ENT.	ENT.	ENT.	ENT.	ENT.
FLOWMETER READING	65	129	NONE		NONE	177	115	85	62	NONE	113	157	73	140	95	102	124	135	168	95	121
WATER FLOW - #/SEC.	.013	.0315				.046	.0275	.0185	.0125		.027	.0397	.0152	.0348	.0217	.0235	.030	.0305	.043	.0217	.0292
SPRAY	YES	YES	YES	UNSTABLE	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	NO	NO	NO	NO	NO	NO	NO
EJECTOR VALVE SET	P.O.	P.O.	P.O.		P.O.	P.O.	P.O.	P.O.	P.O.	F.O.	F.O.	F.O.	F.O.	F.O.	P.O.	P.O.	P.O.	P.O.	P.O.	P.O.	P.O.
AIR FLOW - #/SEC.	.216	.216	.216		.228	.228	.228	.228	.228	.2525	.2525	.2525	.2525	.2525	.2148	.2148	.2148	.2148	.2148	.231	.231
ω = #H₂O/# AIR	0.0602	0.146	0		0	.202	.1207	.0812	.0549	0	.1069	.157	.0615	.1378	.101	.1095	.1395	.142	.200	.094	.126
P_{14}/P_1	.837	.850	.818		.829	.849	.856	.852	.844	.828	.850	.846	.855	.852	.191	.187	.1712	.1685	.162	.190	.1753

RUNS	72-92
DATE	4/4/52
BAROM. PRESS. MM./HG.	762.2

TABLE VI

TABULATION OF DATA FOR SMALL SCALE CONSTANT AREA AEROTHERMOPRESSOR TESTS

M.I.T. - CAMBRIDGE, MASS.

RUN NUMBER	93	94	95	96	97	98	99	100	101	102
INLET TEMP. °R.	1300	1300	1100	1100	1100	1100	537	537	537	537
OUTLET TEMP. °R.	660	560	680	566	560	555	← UNMEASURABLE - AT OR BELOW 460°R			
ROOM TEMP. °F.	81	81	82	82	82	82	77	77	77	77
	←							SUPERSONIC		
PRESSURES - CM. HG. ABS.										
UPPER STAG. CHAMBER	75.3	75.3	75.3	75.3	75.3	75.3	75.1	75.1	75.1	75.0
#2 TAP (THROAT)	~~39.6~~ 40.7	41.2	39.5	40.0	40.5	41.1	33.7	35.7	35.9	41.0
3	11.2	11.3	10.6	10.7	10.9	11.3	10.8	11.0	11.0	11.0
4	11.2	11.5	10.7	10.2	11.4	12.0	10.6	11.6	11.6	21.6*
5	11.7	12.1	11.1	11.7	12.3	12.5	12.1	12.3	12.5	↓
6	11.2	11.2	11.5	11.4	11.6	11.9	12.3	12.3	*	
7	11.6	11.9	12.2	12.1	12.4	12.7	13.7	13.7	↓	
8	11.5	11.6	12.3	12.0	12.2	12.5	14.2	14.7		
9	12.4	12.5	13.5	13.2	13.2	13.2	15.0	18.7*		
10	12.0	12.1	13.2	12.9	12.9	12.9	22.7*	27.7		
11	12.1	12.2	14.1	13.3	13.4	13.4	26.7	28.7		
12	12.2	12.2	14.4	13.5	13.7	13.6	27.7	28.9		
13	12.9	12.9	15.3	14.0	14.2	14.2	28.2	29.0		
14	13.0	13.2	15.7	14.2	14.3	14.3	26.7	27.5		
LOWER STAG. CHAMBER	24.8	26.2	22.2	22.9	23.1	24.1	16.5	16.7	16.7	16.1
EJECTOR TANK	26.7	28.0	24.2	24.9	25.1	25.9	18.6	18.6	18.7	18.2
IMPACT TUBE	48.2	47.7	47.7	47.7	47.2	50.7	38.4	37.7	38.7	38.6
WATER INJECTION:										
POSITION	ENT.	ENT.	ENT.	ENT.	ENT.	ENT.	ENT.	ENT	ENT	ENT
FLOWMETER READING	150	175	82	117	140	175	NONE	20	24	40
WATER FLOW - #/SEC.	.0375	.0455	.0180	.0280	.0348	.0455		.003	.0037	.007
SPRAY	No	No	No	No	No	No	No	No	No	No
EJECTOR VALVE SETTING	P.O	P.O.	P.O.	P.O.	P.O	P.O.	F.O.	F.O.	F.O.	F.O.
AIR FLOW - #/SEC.	.231	.231	.252	.252	.252	.252	.228	.228	.228	.228
ω = # H_2O / # AIR	.1625	.197	.0715	.111	.138	.180	0	.013	.0162	.0307
P_{14}/P_1	.1728	.1752	.208	.1885	.190	.190	.355	.366		

RUN NUMBER	103	104	105	106	107	108	109	110	111	112	113
INLET TEMP. °R.	537	537	537	537	537	537	537	537	537	537	537
OUTLET TEMP. °R.	UNMEASURABLE - AT OR BELOW 460°R						→	500	500	500	500
ROOM TEMP. °F.	77	77	77	77	77	77	77	77	77	77	77
	SUPERSONIC						→	←	SUBSONIC		→
PRESSURES - CM. HG. ABS.											
UPPER STAG. CHAMBER	75.0	75.1	75.2	75.3	75.2	75.3	75.3	75.6	75.6	75.6	75.0
#2 TAP (THROAT)	41.4	42.1	33.1	44.7	34.8	34.6	34.7	37.7	46.2	44.2	45.0
3	11.6	25.6*	10.8	29.5*	10.8	26.6*	36.7*	65.3	65.2	65.1	65.3
4	29.6*	37.9	10.1	38.7	10.6	38.2	40.7	64.8	64.8	64.8	65.2
5	35.6	38.2	11.6	39.2	11.7	38.6	40.2	64.2	64.4	64.5	65.0
6	36.6	37.6	12.3	38.2	12.2	38.1	39.3	63.7	64.0	64.2	64.6
7	36.1	36.9	13.1	37.5	13.3	37.1	38.5	63.2	63.6	63.8	64.3
8	35.6	36.1	13.6	36.6	13.7	36.6	37.7	63.0	63.4	63.6	64.1
9	35.1	35.3	15.1	35.9	15.2	35.7	36.8	62.6	63.1	63.3	63.8
10	34.1	34.2	18.6*	34.7	18.6*	34.6	35.5	61.8?	62.1?	62.4?	64.7?
11	33.8	32.9	24.6	33.5	23.6	33.4	34.2	61.7	62.2	62.6	63.2
12	31.6	31.6	26.8	32.2	27.6	32.1	32.8	60.6?	60.7?	61.2?	63.7?
13	30.4	30.3	27.6	30.8	27.6	30.9	31.5	61.0	61.6	62.0	62.8
14	28.3	28.2	26.6	28.7	26.6	28.7	29.3	60.7	61.2	61.5	62.4
LOWER STAG. CHAMBER	15.8	16.2	15.7	16.7	18.1	20.3	17.2	60.2	60.6	60.9	62.2
EJECTOR TANK	17.9	17.8	18.3	18.1	18.3	18.6	18.6	60.9	61.4	62.8	62.7
IMPACT TUBE	38.4	38.3	36.0	11.7	34.8	16.0	16.3	67.0	67.0	67.2	68.2
WATER INJECTION:											
POSITION	ENT	ENT.	THROAT	THROAT	EXIT	EXIT	EXIT	EXIT	EXIT	EXIT	EXIT
FLOWMETER READING	90	140	NONE	140	NONE	68	140	164	125	65	28
WATER FLOW - #/SEC.	.0[illegible]0	.0345	~~.014~~	.0345		.014	.0345	.042	.030	.013	.0045
SPRAY	No	No	No	No	No	No	No	No	No	No	No
EJECTOR VALVE SETTING	F.O.	F.O.	F.O.	F.O.	F.O.	F.O.	F.O.	P.O.	P.O.	P.O.	P.O.
AIR FLOW - #/SEC.	.228	.228	.228	.228	.228	.228	.228	.228	.227	.227	.227
ω = # H_2O / # AIR	.0877	.1515	0	.1515	0	.0615	.1515	.184	.132	.057	.0197
P_{14}/P_1	.378	.376	.354	.381	.354	.380	.389	.793	.809	.813	.831

RUNS	93-98	99-113
DATE	4/4/52	4/10/52
BAROM. PRESS. mm Hg	762.2	760.3

* DENOTES SHOCK

TABLE VI

TABULATION OF DATA FOR SMALL SCALE CONSTANT AREA AEROTHERMOPRESSOR TESTS

M.I.T. - CAMBRIDGE, MASS.

RUN NUMBER	93	94	95	96	97	98	99	100	101	102	103	104	105	106	107	108	109	110	111	112	113
INLET TEMP. °R.	1300	1300	1100	1100	1100	1100	537	537	537	537	537	537	537	537	537	537	537	537	537	537	537
OUTLET TEMP. °R.	560	560	680	566	560	555	← UNMEASURABLE - AT OR BELOW 460°R →											500	500	500	500
ROOM TEMP. °F.	81	81	82	82	82	82	77	77	77	77	77	77	77	77	77	77	77	77	77	77	77
	←							SUPERSONIC										←	SUBSONIC		→
PRESSURES - CM. HG. ABS.																					
UPPER STAG. CHAMBER	75.3	75.3	75.3	75.3	75.3	75.3	75.1	75.1	75.1	75.0	75.0	75.1	75.2	75.3	75.2	75.3	75.3	75.6	75.6	75.6	75.0
#2 TAP (THROAT)	~~39.5~~ 40.7	41.2	39.5	40.0	40.5	41.1	33.7	35.7	35.9	41.0	41.4	42.1	33.1	44.7	34.8	34.6	34.7	37.7	46.2	44.2	45.0
3	11.2	11.3	10.6	10.7	10.9	11.3	10.8	11.0	11.0	11.0	11.6	25.6*	10.8	29.5*	10.8	26.6*	36.7*	65.3	65.2	65.1	65.3
4	11.2	11.5	10.7	10.2	11.4	12.0	10.6	11.6	11.6	21.6*	29.6*	37.9	10.1	38.7	10.6	38.2	40.7	64.8	64.8	64.8	65.2
5	11.7	12.1	11.1	11.7	12.3	12.5	12.1	12.3	12.5		35.6	38.2	11.6	39.2	11.7	38.6	40.2	64.2	64.4	64.5	65.0
6	11.2	11.2	11.5	11.4	11.6	11.9	12.3	12.3	*		36.6	37.6	12.3	38.2	12.2	38.1	39.3	63.7	64.0	64.2	64.6
7	11.6	11.9	12.2	12.1	12.4	12.7	13.7	13.7			36.1	36.9	13.1	37.5	13.3	37.1	38.5	63.2	63.6	63.8	64.3
8	11.5	11.6	12.3	12.0	12.2	12.5	14.2	14.7			35.6	36.1	13.6	36.6	13.7	36.6	37.7	63.0	63.4	63.6	64.1
9	12.4	12.5	13.5	13.2	13.2	13.2	15.0	18.7*			35.1	35.3	15.1	35.9	15.2	35.7	36.8	62.6	63.1	63.3	63.8
10	12.0	12.1	13.2	12.9	12.9	12.9	22.7*	27.7			34.1	34.2	18.6*	34.7	18.6*	34.6	35.5	61.8?	62.1?	62.4?	64.7?
11	12.1	12.2	14.1	13.3	13.4	13.4	26.7	28.7			33.8	32.9	24.6	33.5	23.6	33.4	34.2	61.7	62.2	62.6	63.2
12	12.2	12.2	14.4	13.5	13.7	13.6	27.7	28.9			31.6	31.6	26.8	32.2	27.6	32.1	32.8	60.6?	60.7?	61.2?	63.7?
13	12.9	12.9	15.3	14.0	14.2	14.2	28.2	29.0			30.4	30.3	27.6	30.8	27.6	30.9	31.5	61.0	61.6	62.0	62.8
14	13.0	13.2	15.7	14.2	14.3	14.3	26.7	27.5			28.3	28.2	26.6	28.7	26.6	28.7	29.3	60.7	61.2	61.5	62.4
LOWER STAG. CHAMBER	24.8	26.2	22.2	22.9	23.1	24.1	16.5	16.7	16.7	16.1	15.8	16.2	15.7	16.7	18.1	20.3	17.2	60.2	60.6	60.9	62.2
EJECTOR TANK	26.7	28.0	24.2	24.9	25.1	25.9	18.6	18.6	18.4	18.2	17.9	17.8	18.3	18.1	18.3	18.6	18.6	60.9	61.4	62.8	62.7
IMPACT TUBE	48.2	47.7	47.7	47.7	47.2	50.7	38.4	37.7	38.7	38.6	38.4	38.3	36.0	11.7	34.8	16.0	16.3	67.0	67.0	67.2	68.2
WATER INJECTION:																					
POSITION	ENT.	ENT.	ENT.	ENT.	ENT.	ENT.	ENT.	ENT	ENT	ENT	ENT	ENT	THROAT	THROAT	EXIT	EXIT	EXIT	EXIT	EXIT	EXIT	EXIT
FLOWMETER READING	150	175	82	117	140	175	NONE	20	24	40	90	140	NONE	140	NONE	68	140	164	125	65	28
WATER FLOW - #/SEC.	.0375	.0455	.0180	.0280	.0348	.0455		.003	.0037	.007	.020	.0345	~~.014~~	.0345		.014	.0345	.042	.030	.013	.0045
SPRAY	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No
EJECTOR VALVE SETTING	P.O.	P.O.	P.O.	P.O.	P.O.	P.O.	F.O.	F.O.	F.O.	F.O.	F.O.	F.O.	F.O.	F.O.	F.O.	F.O.	F.O.	P.O.	P.O.	P.O.	P.O.
AIR FLOW - #/SEC.	.231	.231	.252	.252	.252	.252	.228	.228	.228	.228	.228	.228	.228	.228	.228	.228	.228	.228	.227	.227	.227
ω = # H_2O / # AIR	.1625	.197	.0715	.111	.138	.180	0	.013	.0162	.0307	.0877	.1515	0	.1515	0	.0615	.1515	.184	.132	.057	.0197
P_{14}/P_1	.1728	.1752	.208	.1885	.190	.190	.355	.366			.378	.376	.354	.381	.354	.380	.389	.793	.809	.813	.831

RUNS	93-98	99-113
DATE	4/4/52	4/10/52
BAROM. PRESS. mm Hg	762.2	760.3

* DENOTES SHOCK

TABLE VII

TABULATION OF DATA FOR SMALL SCALE CONSTANT-AREA AEROTHERMOPRESSOR TESTS

MIT-CAMBRIDGE, MASS.

RUN NUMBER	114	115	116	117	118	119	120	121	122	123	124	125
INLET TEMP. °R.	1500	1500	1500	1500	1500	1500	1500	1500	1500	1500		
OUTLET TEMP. °R	605	760	950	670	1265	600	750	925	705	1265		
ROOM TEMP. °F.	78	78	78	80	80	77	78	78	79	80		
	←				SUBSONIC					→		
PRESSURES - CM. HG. ABS.												
UPPER STAG. CHAMBER	75.5	75.4	75.4	75.4	75.4	75.2	75.2	75.2	75.2	75.2		
#2 TAP (THROAT)	42.2	42.3	42.3	42.3	42.3	47.1	47.1	47.1	47.1	47.1		
3	64.0	63.8	64.3	63.8	64.4	63.7	64.8	65.2	64.6	66.0		
4	64.0	63.8	64.1	63.8	64.3	64.6	65.4	65.5	65.1	65.8		
5	64.1	64.0	64.0	63.8	64.1	64.8	65.5	65.6	65.3	65.7		
6	64.2	64.0	63.9	63.8	63.8	64.9	65.4	65.5	65.2	65.5		
7	64.2	63.9	63.8	63.7	63.5	64.8	65.3	65.3	65.2	65.1		
8	64.2	63.9	63.7	63.6	63.3	64.8	65.3	65.2	65.1	64.7		
9	64.2	63.8	63.5	63.5	63.0	64.7	65.2	65.0	65.1	64.5		
10	64.1	63.7	63.3	63.4	62.6	64.6	65.1	64.9	64.9	64.2		
11	64.0	63.5	63.1	63.2	62.1	64.4	64.9	64.6	64.8	63.8		
12	63.9	63.4	63.0	63.2	61.9	64.3	64.7	64.4	64.7	63.5		
13	63.9	63.3	62.8	63.1	61.5	64.2	64.6	64.3	64.6	63.3		
14	63.6	63.1	62.5	62.9	61.0	63.8	64.3	64.0	64.4	62.9		
LOWER STAG. CHAMBER	63.4	62.8	62.0	62.5	60.5	63.6	64.0	63.6	64.1	62.4		
EJECTOR TANK	65.1	63.6	63.1	63.3	61.3	64.5	64.8	64.1	64.[illegible]	63.1		
IMPACT TUBE	68.5	68.2	68.1	68.0	67.6	68.2	68.6	68.6	68.7	68.6		
WATER INJECTION												
POSITION	EXIT	EXIT	EXIT	EXIT	EXIT	THROAT	THROAT	THROAT	THROAT	THROAT		
FLOWMETER READING	168	124	95	145	NONE	171	119	87	139	NONE		
WATER FLOW - #/SEC.	.0432	.030	.0206	.0363		.044	.0285	.019	.0395			
SPRAY	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES		
EJECTOR VALVE SETTING	P.O.	P.O.	P.O.	P.O.	P.O.	P.O.	P.O.	P.O.	P.O.	P.O.		
AIR FLOW - #/SEC.	.214 ~~.178~~	.214 ~~.178~~	.214 ~~.178~~	.214 ~~.178~~	.214 ~~.214~~	.2133	.2133	.2133	.2133	.2133		
ω = #H$_2$O/#AIR	.202 ~~.243~~	.190 ~~.169~~	.0962	.169	0	.206	.1338	.0892	.162	0		
P_{14}/P_1	.843	.836	.830	.835	.809	.850	.856	.851	.858	.836		

	DATE	BAROMETRIC PRESS.
RUNS # 114-118	4/10/52	760.3 MM. HG.
117-123	4/16/52	758.65

APPENDIX C

THEORETICAL ANALYSIS

NOMENCLATURE

A	cross-sectional area
C	speed of sound
D	test section diameter
f	friction coefficient of duct $(T_w / \frac{1}{2} \rho V^2)$
h	enthalpy per unit mass
k	ratio of specific heat (c_p/c_v)
M	mach number
L	length of test section
P	static pressure
P_o	isentropic stagnation pressure
T	absolute temperature
T_o	absolute stagnation temperature
R	gas constant
V	velocity of stream
w	mass rate of flow
$\mathcal{W}$	molecular weight
ρ	mass density of stream
τ_o	shearing stress on walls of duct
ω	ratio of mass rate of flow of evaporated liquid to mass rate of flow of gas
ω_ℓ	ratio of mass rate of flow of liquid to mass rate of flow of gas
$(\ )_1$	refers to section 1, test section entrance
$(\ )_2$	refers to section 2, test section exit
$(\ )_a$	refers to gas
$(\ )_s$	refers to evaporated liquid
$(\ )_\ell$	refers to liquid

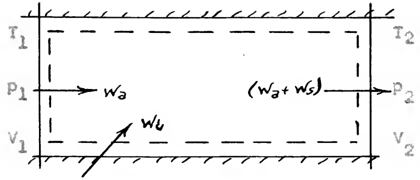
APPENDIX C

Theoretical Analysis

I. Analysis of Compressible Flow Constant Area Process

Assumptions:
(1) Adiabatic
(2) Liquid Velocity = 0
(3) Wall Friction Included

A. Complete Evaporation at Section 2.



$$\text{let } \omega_2 = \frac{w_s}{w_a}$$

Continuity:

$$w_a = \rho_1 V_1 A \qquad (3)$$

$$1 + \omega_2 = \rho_2 V_2 A$$

$$1 + \omega_2 = \frac{\rho_2 V_2}{\rho_1 V_1} \qquad (4)$$

Equation of State:

$$\frac{p_2}{p_1} = \frac{\rho_2 W_a T_2}{\rho_1 W_m T_1} \qquad (5)$$

Gibbs - Dalton:

$$W_m = W_a \left[\frac{1 + \omega_2}{1 + \frac{W_a}{W_s} \omega_2} \right] \qquad (6)$$

<u>Combining (4), (5), and (6):</u>

$$1 + \frac{W_a}{W_s}\,\omega_2 = \frac{V_2}{V_1}\,\frac{p_2}{p_1}\,\frac{T_1}{T_2} \tag{7}$$

<u>Momentum:</u>

$$p_1 A - p_2 A - \int_1^2 \tau_w\, \pi D\, dL = (W_a + W_s)\, V_2 - W_a V_1$$

$$\text{or} \quad p_1 - p_2 = \int_1^2 \frac{4\tau_w}{D}\, dL = \frac{W_a}{A}\left[(1 + \omega_2)\, V_2 - V_1\right]$$

<u>Definition of f:</u>

$$f = \frac{\tau_w}{\frac{\rho}{2} V^2} = \frac{\tau_w}{\frac{W_a V}{2A}\,(1 + \omega)}$$

$$\int_1^2 \frac{4\tau_w}{D}\, dL \approx \frac{fL}{D}\,\frac{2W_a}{A}\left(1 + \frac{\omega_2}{2}\right)\left(\frac{V_1 + V_2}{2}\right)$$

$$\therefore\; p_1 - p_2 - \frac{fL}{D}\,\frac{W_a}{A}\left(1 + \frac{\omega_2}{2}\right)\left(V_1 + V_2\right) = \frac{W_a}{A}\left[(1 + \omega_2)\, V_2 - V_1\right] \tag{8}$$

<u>Combining (3) and (8):</u>

$$1 - \frac{p_2}{p_1} - \frac{fL}{D}\,\frac{\rho_1 V_1^2}{p_1}\left(1 + \frac{\omega_2}{2}\right)\left(1 + \frac{V_2}{V_1}\right) = \frac{\rho_1 V_1^2}{p_1}\left[(1 + \omega_2)\frac{V_2}{V_1} - 1\right] \tag{9}$$

<u>Mach No.:</u>

$$M = \frac{V}{C}\;; \quad C = \sqrt{K R T}$$

$$\rho_1 V_1^2 = \frac{K_1 p_1 V_1^2}{K_1 R\, T_1} = K_1 p_1 M_1^2 \tag{10}$$

<u>Combining (9), (10) and (7):</u>

$$\frac{p_2}{p_1} = 1 - K_1 M_1^2\left[(1 + \omega_2)\,\frac{V_2}{V_1} - 1 + \frac{fL}{D}\left(1 + \frac{\omega_2}{2}\right)\left(1 + \frac{V_2}{V_1}\right)\right] =$$

$$= \frac{V_1}{V_2}\,\frac{T_2}{T_1}\left(1 + \frac{W_a}{W_s}\,\omega_2\right) \tag{11}$$

<u>Solving for $\frac{V_2}{V_1}$</u> :

$$\frac{V_2}{V_1} = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a}$$

$$b = K_1 M_1^2 \left[1 - \frac{fL}{D} \left(1 + \frac{\omega_2}{2} \right) \right] + 1$$

$$a = K_1 M_1^2 \left[1 + \omega_2 + \frac{fL}{D} \left(1 + \frac{\omega_2}{2} \right) \right] \qquad (12)$$

$$c = \frac{T_2}{T_1} \left[1 + \frac{W_a}{W_s} \omega_2 \right]$$

<u>Energy</u>:

$$W_a h_{a_1} + W_\ell h_{\ell_1} + W_a \frac{V_1^2}{2} = W_a h_{a_2} + W_s h_s + (W_a + W_s) \frac{V_2^2}{2}$$

$$(h_{a_2} - h_{a_1}) + \omega_2 (h_{s_2} - h_{\ell_1}) + (1 + \omega_2) \frac{V_2^2}{2} - \frac{V_1^2}{2} = 0$$

Rewriting:

$$\frac{(h_{a2} - h_{a1}) + \omega_2 (h_{s2} - h_{\ell 1})}{\frac{V_1^2}{2}} + 1 + \omega_2 \left(\frac{V_2}{V_1} \right)^2 - 1 = 0 \qquad (13)$$

(12) and (13) combined to give working equation. Resultant equation solved by trial and error obtaining values of ω_2 for assumed values of T_2.

Values of ω_2 obtained from $\omega_2 = 0$ to $\omega_2 = \omega_{g2}$

where $\omega_{g2} = \frac{0.622\, p_{g2}}{p_2 - p_{g2}}$ and $h_{s2} = h_{g2}$

Since p_1, T_1, V_1, and M_1 are known initial conditions and T_2 assumed, p_2, V_2, and M_2 may be obtained from the above relations for a particular ω_2. p_{01}, T_{01}, P_{02}, and T_{02} are obtained from the following relations:

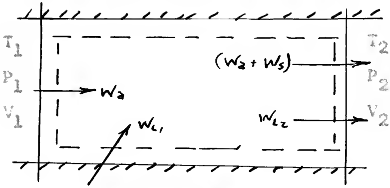
$$\frac{T_o}{T} = 1 + \frac{\bar{K} - 1}{2} M^2 \qquad (14)$$

$$\left(\frac{P_o}{P}\right) = \left(\frac{T_o}{T}\right)^{\frac{\bar{K}}{\bar{K} - 1}} \qquad (15)$$

where: $$\bar{K} = \frac{K_o + K}{2} \qquad (16)$$

and: $$\frac{K}{K - 1} = \frac{1}{.621 + \omega}\left[.621 \frac{K_a}{K_a - 1} + \omega \frac{K_s}{K_s - 1}\right] \qquad (17)$$

B. Incomplete Evaporation at Section 2.



let $\omega_2 = \frac{W_s}{W_a}$

$\omega_{L1} = \frac{W_{L1}}{W_a}$

Equations (3) - (7) from previous Analysis.

<u>Momentum</u>:

Equation (3) rewritten:

$$P_1 - P_2 - \frac{fL}{D} \frac{W_a}{A}\left(1 + \frac{\omega_2}{2}\right)(V_1 + V_2) = \frac{W_a}{A}\left[(1 + \omega_{L1}) V_2 - V_1\right] \qquad (18)$$

Combining (10) and (18) and rewriting:

$$\frac{V_2}{V_1} = \frac{\frac{1}{K_1 M_1^2}\left[1 - \frac{p_2}{p_1}\right] + 1 - \frac{fL}{D}\left(1 + \frac{\omega_2}{2}\right)}{(1 + \omega_{L1}) + \frac{fL}{D}\left(1 + \frac{\omega_2}{2}\right)} \qquad (19)$$

Combining (19) and (7):

$$\frac{p_2}{p_1}^2 - \left[1 + K_1 M_1^2 \left\{1 - \frac{fL}{D}\left(1 + \frac{\omega_2}{2}\right)\right\}\right]\frac{p_2}{p_1} + K_1 M_1^2 \frac{T_2}{T_1}$$

$$\left(1 + \frac{W_a}{W_s}\omega_2\right)\left[1 + \omega_{L_1} + \frac{fL}{D}\left(1 + \frac{\omega_2}{2}\right)\right] = 0 \qquad (20)$$

Solving for p_2/p_1:

$$\frac{p_2}{p_1} = + \beta \pm \sqrt{\beta^2 - \gamma}$$

where: $$\beta = \frac{1}{2}\left[1 + K_1 M_1^2 \left\{1 - \frac{fL}{D}\left(1 + \frac{\omega_2}{2}\right)\right\}\right] \qquad (21)$$

$$\gamma = K_1 M_1^2 \frac{T_2}{T_1}\left(1 + \frac{W_a}{W_s}\omega_2\right)\left[(1 + \omega_{L2}) + \frac{fL}{D}\left(1 + \frac{\omega_2}{2}\right)\right]$$

<u>Energy</u>:

$$w_a h_{a1} + w_{L1} h_{L1} + w_a \frac{V_1^2}{2} = w_a h_{a2} + w_{s2} h_{s2} + (w_{L1} - w_{s2}) h_{L2} + (w_a + w_{L1}) \frac{V_2^2}{2}$$

$$(h_{a2} - h_{a1}) + \omega_2(h_{s2} - h_{L1}) + (\omega_{L1} - \omega_2)(h_{L2} - h_{L1}) = (1 + \omega_{L1}) \frac{V_2^2}{2} - \frac{V_1^2}{2} \qquad (22)$$

Solving (22) for $\frac{V_2}{V_1}$:

$$\frac{V_2}{V_1} = \sqrt{\frac{(h_{s2} - h_{s1}) + \omega_2(h_{s2} - h_{L1}) + (\omega_{L1} - \omega_2)(h_{L2} - h_{L1})}{(1 + \omega_{L1}) \frac{V_1{}^2}{w_2}} + \frac{1}{1 + \omega_{L1}}} \tag{23}$$

Combining (7) and (23):

$$\frac{p_2}{p_1} = \frac{1 + \frac{W_a}{W_s}\omega'_2 \quad \frac{T_2}{T_1}}{\sqrt{\frac{1}{1 + \omega_{L1}} + \frac{(h_{s2} - h_{s1}) + \omega_2(h_{s2} - h_{L1}) + (\omega_{L1} - \omega_2)(h_{L2} - h_{L1})}{(1 + \omega_{L1}) \frac{V_1{}^2}{2}}}} \tag{24}$$

The graphical solution of (21) and (24) for various assumed values of T_2, gives a plot of the variation of P_2/p_1 versus ω_2 for a particular value of ω_{L1}. Values of ω_2 were plotted from $\omega_2 = 0$ to $\omega_2 = \omega_{L1}$.

TABLE VIII

TABULATION OF INLET CONDITIONS FOR THEORETICAL ANALYSIS

Initial Conditions Calculated Runs

	Run No. 48	Run No. 118
Mach No. (M_1)	.382	1.80
Stagnation Temp. (T_{01})	1500°R	1500°R
Stagnation Press. (P_{01})	14.56 Psia	14.50 Psia
Temperature (T_1)	1460°R	940°R
Pressure (p_1)	12.42 Psia	2.24 Psia
Ratio of Specific Heats (k_1)	1.351	1.367
Mass Rate of Flow (w_a)	.178 $\frac{\text{lbs.air}}{\text{sec.}}$	.2135 $\frac{\text{lbs.air}}{\text{sec.}}$
Friction Factor (f)	.0048	.0030

APPENDIX D

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BIBLIOGRAPHY

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